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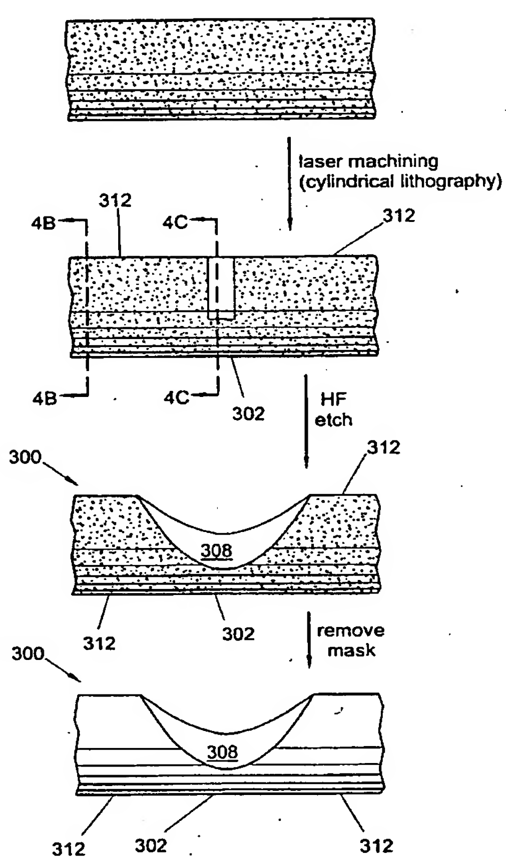

(57) Abstract: A fiber-optic waveguide comprises a transverse-optical-coupling fiber segment (312) and first and second longitudinally adjacent fiber segments. The cladding layers of the adjacent segments surround the cores and encompass an optical mode propagating through the waveguide. The cladding layer of the coupling segment is asymmetrically disposed about the core, thereby yielding a coupling surface (308) and enabling the propagating optical mode to extend beyond the coupling surface. The fiber-optic waveguide may be incorporated into an optical power control device by tangentially engaging the coupling surface with a circumferential-mode optical resonator, thereby enabling control of optical power transmitted through the waveguide via modulation of circumferential-mode resonator properties and/or coupling thereto. The fiber-optic waveguide may be fabricated by circumferentially asymmetric removal of cladding material form the coupling segment. The cladding material may be removed by providing a mask, such a carbon outer fiber coatting, polymer jacket, photoresist or metal, and etching the cladding layer material ("side-etching"), for example by HF, to form the asymmetric cladding profile, auch as a saddle-like shape.

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FIBER-OPTIC WAVEGUIDES FOR TRANSVERSE OPTICAL COUPLING

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RELATED APPLICATIONS

This application claims benefit of prior filed co-pending U. S. provisional Application No. 60/226,147 entitled "Fiber-optic waveguides for evanescent optical coupling and methods of fabrication and use thereof", filed 08/18/2000 in the names of Peter C. Sercel, Guido Hunziker, and Robert B. Lee, said provisional application being hereby incorporated by reference as if fully set forth herein.

GOVERNMENT RIGHTS

The U.S. Government may have limited rights in this application pursuant to Office of Naval Research Contract No. N00014-00-1-0072 via California Institute of Technology Subcontract No. 1008921.

FIELD OF THE INVENTION

The field of the present invention relates to optical fiber telecommunications and sensors. In particular, apparatus and methods are described herein for transverse optical coupling of an optical fiber to a circumferential-mode optical resonator or other optical waveguide and/or resonator.

BACKGROUND

This application is related to subject matter disclosed in:

A1) U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic modulator" filed 7 DEC 1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A2) U.S. Application No. 09/454,719 entitled "Resonant optical wave power control devices and methods" filed 7 DEC 1999 in the names of Kerry J. Vahala and

Amnon Yariv, said application being hereby incorporated by reference in its entirety as if fully set forth herein;

A3) U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-microsphere coupler" filed 13 NOV 1998 in the names of Kerry J. Vahala and Ming Cai, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein;

A4) U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed 12 NOV 1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said application being hereby incorporated by reference in its entirety as if fully set forth herein; and

A5) U.S. provisional Application No. 60/183,499 entitled "Resonant optical power control devices and methods of fabrication thereof" filed 17 FEB 2000 in the names of Peter C. Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

A6) U.S. provisional application entitled "Fiber-optic waveguides for evanescent optical coupling and methods of fabrication and use thereof", filed 18 AUG 2000 in the names of Peter C. Sercel, Guido Hunziker, and Robert B. Lee, Application No. 60/226,147, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

A7) U.S. provisional Application No. 60/257,248 entitled "Modulators for resonant optical power control devices and methods of fabrication and use thereof" filed 21 DEC 2000 in the names of Oskar J. Painter, Peter C. Sercel, Kerry J. Vahala, and Guido Hunziker, said provisional application being hereby incorporated by reference as if fully set forth herein.

A8) U.S. provisional application entitled "Waveguides and resonators for integrated optical devices and methods of fabrication and use thereof", filed 21 DEC 2000 in the name of Oskar J. Painter, Application No. 60/257,218, said provisional application being hereby incorporated by reference as if fully set forth herein.

A9) U.S. utility patent Application No. 09/788,303 entitled "Cylindrical processing of a optical media" filed 16 FEB 2001 in the names of Peter C. Sercel, Kerry J. Vahala, David W. Vernooy, and Guido Hunziker, said application being hereby incorporated by reference as if fully set forth herein.

A10) U.S. utility patent Application No. 09/788,331 entitled "Fiber-ring optical resonators" filed 16 FEB 2001 in the names of Peter C. Sercel, Kerry J. Vahala, David W. Vernooy, Guido Hunziker, and Robert B. Lee, said application being hereby incorporated by reference as if fully set forth herein.

A11) U.S. utility patent Application No. 09/788,300 entitled "Resonant optical filter" filed 16 FEB 2001 in the names of Kerry J. Vahala, Peter C. Sercel, David W. Vernooy, Oskar J. Painter, and Guido Hunziker, said application being hereby incorporated by reference as if fully set forth herein.

A12) U.S. utility patent Application No. 09/788,301 entitled "Resonant optical power control device assemblies" filed 16 FEB 2001 in the names of Peter C. Sercel, Kerry J. Vahala, David W. Vernooy, Guido Hunziker, Robert B. Lee, and Oskar J. Painter, said application being hereby incorporated by reference as if fully set forth herein.

A13) U.S. provisional Application No. 60/170,074 entitled "Optical routing/switching based on control of waveguide-ring resonator coupling", filed 9 DEC 1999 in the name of Amnon Yariv, said provisional application being hereby incorporated by reference in its entirety as if fully set forth herein.

This application is also related to subject matter disclosed in the following 7 publications, each of said 7 publications being hereby incorporated by reference in its entirety as if fully set forth herein:

P1) Ming Cai, Guido Hunziker, and Kerry Vahala, "Fiber-optic add-drop device based on a silica microsphere whispering gallery mode system", IEEE Photonics Technology Letters Vol. 11 686 (1999);

P2) J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phased-matched excitation of whispering gallery-mode resonances by a fiber taper", Optics Letters Vol. 22 1129 (1997);

P3) Serpenguzel, S. Arnold, and G. Griffel, "Excitation of resonances of microspheres on an optical fiber", Opt. Lett. Vol. 20, 654 (1995);

P4) F. Treussart, N. Dubreil, J. C. Knight, V. Sandoghar, J. Hare, V. Lefevre-Seguin, J. M. Raimond, and S. Haroche, "Microlasers based on silica microspheres", Ann. Telecommun. Vol. 52, 557 (1997); and

P5) M. L. Gorodetsky, A. A. Savchenkov, V. S. Ilchenko, "Ultimate Q of optical microsphere resonators", Optics Letters, Vol. 21, 453 (1996).

P6) Ming Cai, Oskar Painter, and Kerry J. Vahala, "Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system", Physical Review Letters, Vol. 85(1) 74 (2000).

P7) S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, "Whispering-gallery mode microdisk lasers", Applied Physics Letters, Vol. 60, 289 (1992).

Optical fiber and propagation of high-data-rate optical pulse trains therethrough has become the technology of choice for high speed telecommunications. Wavelength division multiplexing (WDM) techniques are now commonly used to independently transmit a plurality of signals over a single optical fiber, independent data streams being carried by optical fields propagating through the optical fiber at a slightly differing optical carrier wavelengths (i.e., signal channels). WDM techniques include dense wavelength division multiplexing (DWDM) schemes, wherein the frequency spacing between adjacent signal channels may range from a few hundred GHz down to a few GHz. A propagating mode of a particular wavelength must be modulated, independently of other propagating wavelengths, in order to carry a signal. A signal carried by a particular wavelength channel must be independently accessible for routing from a particular source to a particular destination. These requirements have previously required complex and difficult-to-manufacture modulating and switching devices requiring extensive active alignment procedures during fabrication/assembly, and as a result are quite expensive. Such devices may require conversion of the optical signals to electronic signals and/or vice versa, which is quite power consuming and inefficient. In the patent applications A1 through A13 cited above a new approach has been disclosed for controlling optical power transmitted through an optical fiber that relies on the use of resonant circumferential-mode optical resonators, or other optical resonators, for direct optical coupling to a propagating mode of an optical fiber resonant with the optical resonator, thereby enabling wavelength-specific modulation, switching, and routing of optical signals propagating through the optical fiber. A thorough discussion of the features and advantages of such optical power control devices and techniques, as well as methods of fabrication, may be found in these applications, already incorporated by reference herein.

One important element of these latter devices is optical coupling between a fiber-optic waveguide and a circumferential-mode optical resonator (also referred to as a whispering-gallery mode optical resonator, WGM optical resonator, and so on). The circumferential-mode optical resonator provides wavelength specificity, since only propagating optical modes substantially resonant with the circumferential-mode optical resonator will be significantly affected by the device. A fiber-optic waveguide for transmitting the optical signal through the control device is typically provided with a transverse-optical-coupling segment (i.e., an evanescent-optical-coupling segment), where a portion of the propagating optical mode overlaps a portion of a circumferential optical mode of the circumferential-mode optical resonator, thereby optically coupling the circumferential-mode optical resonator and the fiber-optic waveguide. The transverse-optical-coupling segment may take one of several forms, including an optical fiber taper, D-shaped optical fiber, an optical fiber with a saddle-shaped concavity in the cladding layer, and/or other functionally equivalent configurations. These are discussed in detail in patent applications A1 through A7 cited herein. Fiber-optic waveguides having a transversely-asymmetric transverse coupling segments (saddle-shaped, for example) and methods of fabrication and/or use thereof form the subject matter of the present application.

A circumferential-mode optical resonator structure may comprise a glass micro-sphere or micro-disk, a fiber-ring resonator, a semiconductor ring/waveguide, or other functionally equivalent structure, described in detail in earlier-cited applications A1 through A12. A high-Q circumferential-mode optical resonator supports relatively narrow-linewidth resonant circumferential optical modes (i.e., having a linewidth consistent with typical linewidths of a WDM system, TDM system, or other optical data transmission system), which in an optical power control device may optically couple to propagating optical modes of the fiber-optic waveguide of substantially resonant optical wavelength. The circumferential-mode optical resonator therefore provides the wavelength selectivity of the optical power control device. Non-resonant propagating optical signals pass by the circumferential-mode optical resonator relatively undisturbed, and are transmitted through the device. The effect of the device on a substantially resonant signal channels depends on the nature of the control device.

A resonant optical filter may be constructed by coupling a second optical waveguide to the resonator to a similar degree that the fiber-optic waveguide is optically

coupled to the resonator. In this case a near-critical-coupling condition exists between the resonator and fiber-optic waveguide, and for this condition substantially all of the resonant optical signal will be transferred from the fiber-optic waveguide to the second waveguide. Such a configuration is useful for constructing channel slicer/interleavers or channel add/drop filters for WDM and/or WDM optical transmission systems. Such a device enables wavelength-specific routing of one or more resonant signal channels among group of signal channels.

Alternatively, a resonant optical modulator or switch may be constructed by providing the circumferential-mode optical resonator with an optical loss mechanism that may be actively controlled or modulated. By modulating the resonator loss between critical-coupling and either over- or under-coupling, the transmission of a resonant signal channel may be selectively modulated between near-zero transmission and non-zero transmission. Since the circumferential-mode optical resonator provides wavelength (i.e., signal channel) specificity, the optical loss mechanism need not be wavelength specific.

Tapered fiber-optic waveguides are typically preferred for optically coupling to a circumferential-mode optical resonator, and exhibit several advantages over the conventional prism-coupling scheme for coupling to circumferential-mode resonators (as disclosed, for example, by Gorodetsky et al, cited hereinabove). These advantages include: 1) No sophisticated optical coupling assembly is required as input and output light is always guided and manipulated in optical fiber; 2) Insertion losses into/out of tapered single mode fiber can be extremely low and spectrally nearly uniform (insertion losses as low as 0.1 dB are routinely demonstrated); 3) Highly efficient optical coupling may be achieved between a fiber-optic taper and other optical waveguide or optical resonator elements (as in publications P1 and P6); and 4) The system is inherently robust owing to its all fiber optic construction.

Difficulties may arise, however, with the use of tapered fiber-optic waveguides for optical coupling to circumferential-mode optical resonators (such as micro-spheres, micro-disks, micro-rings, and/or fiber rings) or to other optical waveguide and/or resonators. These include:

A. *Difficulty in producing polarization maintaining tapered fiber:*

It may be difficult to prepare fiber-optic tapers using polarization-maintaining (PM) optical fiber. In many applications of optical power control devices in

telecommunications or sensor applications, it is important to use PM fiber, since resonant circumferential optical modes in spheres, disks, and rings are generally polarization dependent, as are optical modes of other optical waveguides and/or resonators. PM fiber is necessary to guarantee that optical power may be launched into the taper with a suitably specified polarization state, so as to couple to a particular circumferential optical mode of the circumferential-mode resonator structure, for example. Such PM fiber, including standard bowtie or panda (shown in cross-section in Fig. 1) fiber designs, is fabricated with internal longitudinal stressor elements 105 surrounding the core 104, the stressor elements typically being composed of doped silicate glass (e.g., borosilicate glass) having mechanical properties and/or melting point substantially differing from the surrounding silica cladding 106, complicating the process of pulling low-loss tapers in these fibers.

A possible solution to this problem of fabricating PM fiber tapers would be splicing a section of standard fiber (i.e., non-polarization-maintaining fiber, having a substantially homogeneous cladding layer with no stressor elements) into a length of PM fiber and pulling the tapered section in the standard fiber segment. Provided the spliced-in section is sufficiency short, an optical mode propagating through the tapered segment should experience minimal randomization of polarization. However, the two opposing sections of PM fiber must be rotationally aligned to high precision (1° or better), which represents a significant manufacturing problem if the spliced-in standard fiber segment has any appreciable length (greater than about 1 mm, for example).

B. *Difficulty in handling and assembling structures containing tapered fiber due to the fragility and flexibility of tapers:*

Tapered optical fibers, in order to be useful as transverse-optical-coupling members for wavelength bands currently most relevant to fiber-optic telecommunications (about 0.8 μm to about 1.7 μm), must be prepared with a taper diameter of about 1-3 μm, and are consequently extremely flexible. Thus for example, even when the non-tapered sections of a tapered fiber are placed coaxially in an alignment groove, the tapered section may sag or bow so that it is not positioned coaxially with respect to the non-tapered sections. This may render problematic the production of mechanically rigid, stable assemblies comprising micro-spheres, micro-rings, micro-disks, fiber rings, and/or other circumferential-mode resonator structures and the tapered optical fiber waveguide member. Also, by virtue of the small diameter, a tapered optical fiber is extremely fragile.

It may therefore be difficult to place, without breakage, the fiber taper within an alignment fixture such as a groove machined into a rigid substrate, as described for example in U.S. provisional Application Nos. 60/183,499 and 60/226,147 cited hereinabove.

For these reasons it may be considered preferable to use a "D"-shaped optical fiber as a waveguide coupling member instead of an optical fiber taper as shown in Fig.2. In such a D-fiber 200, the fiber has a D-shaped cross-section such that the fiber core 202 is sufficiently near to the flat side of the "D" that an optical mode propagating along the fiber has an evanescent wave portion extending transversely beyond the flat side of the "D". Upon assembly of an optical power control device, the D-shaped transmission optical fiber and the circumferential-mode resonator structure 204 may each be positioned and secured in respective alignment grooves and so that the circumferential-mode resonator structure is in substantial tangential engagement (in mechanical contact, for example) with the flat portion of the "D". As described earlier in U.S. provisional Application No. 60/183,499, appropriate depths of the alignment grooves of a substrate, along with mating alignment structures on adjacent fiber segments and the resonator-alignment grooves may be employed to enable reproducible, reliable, and stable optical coupling of the circumferential-mode and the D-shaped transmission fiber without resort to complicated and/or labor-intensive active alignment procedures. Advantages of this approach are: 1) mechanical stability and ease of placement of the D-fiber coupling member; 2) D-fibers which are polarization maintaining are commercially available (e.g. from KVH Industries, Inc.).

There is however one significant disadvantage to the use of D-shaped fiber: it is difficult to achieve a low-loss, mechanically robust fusion splice between D-fiber and ordinary optical fiber of substantially circular cross-section, either PM or standard. This disadvantage translates into increased manufacturing costs and degraded performance (particularly insertion loss) of any device such as a modulator, add-drop filter, or sensor that is based on optical coupling between a circumferential-mode optical resonator structure and a D-fiber. One means for circumventing this difficulty is use of a standard fiber or PM fiber of circular cross-section and mechanically polishing a flat surface parallel to the fiber axis so as to achieve a D-shaped cross section over a finite length of the fiber. This means was disclosed in publications 3) and 4) cited hereinabove. While this technique has been shown to be effective in those publications (that is, effective in producing all-fiber members for coupling to circumferential-mode structures), the

mechanical polishing necessary is laborious and difficult to control with precision (the distance between the fiber core and the flat of the "D" must be controlled to sub-micrometer precision in order to achieve reproducible controlled optical coupling between the waveguide and the circumferential-mode structure).

It is therefore desirable to provide a fiber-optic waveguide for transverse optical coupling to a circumferential-mode optical resonator, and methods of fabrication and use thereof, wherein:

The fiber-optic waveguide is mechanically stable and robust, thereby enabling reliable, reproducible, and stable optical coupling between the fiber-optic waveguide and a circumferential-mode optical resonator and facilitating handling of the waveguide and fabrication and/or assembly of an optical power control device without excessively frequent breakage of the waveguide.

The fiber-optic waveguide may be readily and reproducibly manufactured, and readily and reproducibly incorporated into an optical power control device using substantially passive alignment techniques.

The fiber-optic waveguide may be readily and reproducibly inserted into polarization-maintaining optical fiber with relatively low insertion loss (less than about 3 dB) using standard optical-fiber splicing techniques.

SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of fiber-optic waveguides for transverse optical coupling and optical power control devices, and in addition may meet one or more of the following objects:

To provide a fiber-optic waveguide for transverse optical coupling;

To provide a fiber optic-waveguide for transverse optical coupling to a circumferential-mode optical resonator;

To provide a fiber-optic waveguide for transverse optical coupling that is polarization-maintaining;

To provide a fiber-optic waveguide for transverse optical coupling that may be readily and reproducibly inserted into polarization-maintaining optical fiber with low insertion loss by standard fiber-optic splicing techniques;

To provide a fiber-optic waveguide for transverse optical coupling that is sufficiently mechanically robust to enable reliable, reproducible, and stable transverse optical coupling between the fiber-optic waveguide and a circumferential-mode optical resonator;

To provide a fiber-optic waveguide for transverse optical coupling that is sufficiently mechanically robust to resist or substantially prevent breakage during handling of the waveguide and/or incorporation of the waveguide into an optical power control device;

To provide a fiber-optic waveguide for transverse optical coupling wherein a portion of the cladding layer of a transverse-optical-coupling segment of a fiber-optic waveguide has been removed and the remaining cladding layer material is asymmetrically disposed about the core;

To provide a fiber-optic waveguide for transverse optical coupling wherein cladding layer material is removed from the transverse-optical-coupling segment of a fiber-optic waveguide by spatially-selective masking of the cladding layer and etching of the cladding material;

To provide methods for fabricating a fiber-optic waveguide wherein the shape of a coupling portion of the cladding layer surface of the transverse-optical-coupling segment of a fiber-optic waveguide is adapted for facilitating reliable, reproducible, and stable optical coupling between the waveguide and an optical waveguide and/or resonator;

To provide methods for fabricating a fiber-optic waveguide wherein the shape of a coupling portion of the cladding layer surface of the transverse-optical-coupling segment of a fiber-optic waveguide is adapted for facilitating reliable, reproducible, and stable optical coupling between the waveguide and a circumferential-mode optical resonator;

To provide a fiber-optic waveguide for transverse optical coupling adapted for enabling reliable, reproducible, and stable optical coupling between the waveguide and a circumferential-mode optical resonator by substantially passive alignment;

To provide a fiber-optic waveguide for transverse optical coupling fabricated from polarization-maintaining optical fiber;

To provide a fiber-optic waveguide for transverse optical coupling fabricated from polarization-maintaining optical fiber, wherein the stressor elements of the polarization-maintaining optical fiber extend transversely beyond the cladding layer surface, thereby providing passive alignment structures for enabling passive alignment of the waveguide with a circumferential-mode optical resonator;

To provide methods for fabricating a fiber-optic waveguide for transverse optical coupling that achieves one or more of the foregoing objects; and

To provide an optical power control device, and methods of fabrication and/or assembly thereof, incorporating a fiber-optic waveguide that achieves one or more of the foregoing objects.

One or more of the foregoing objects may be achieved in the present invention by a fiber-optic waveguide comprising: 1) a transverse-optical-coupling fiber segment; and 2) first and second longitudinally adjacent fiber segments joined to the ends of the transverse-optical-coupling fiber segment and having cores that form, with the core of the transverse-

optical-coupling fiber segment, a substantially continuous core of the fiber-optic waveguide. The cladding layers of the adjacent fiber segments substantially surround the cores thereof and transversely substantially encompass an optical mode propagating through the fiber-optic waveguide. The cladding layer of the transverse-optical-coupling fiber segment is asymmetrically disposed about at least a portion of the core thereof, thereby yielding a coupling portion of the cladding layer surface and enabling a portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment. The fiber-optic waveguide may be incorporated into an optical power control device by tangentially engaging the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment with a circumferential-mode optical resonator, thereby enabling control of optical power transmitted through the fiber-optic waveguide via modulation of circumferential-mode resonator properties and/or coupling thereto. The fiber-optic waveguide may be fabricated by circumferentially asymmetric removal of cladding material from the transverse-optical-coupling fiber segment. The cladding material may be removed by providing a mask for the adjacent fiber segments and a portion of the length and circumference of the transverse-optical-coupling fiber segment, and etching the cladding layer material.

Additional objects and advantages of the present invention may become apparent upon referring to the preferred and alternative embodiments of the present invention as illustrated in the drawings and described in the following written description and/or claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows a transverse-sectional view of standard panda-type polarization-maintaining (PM) optical fiber.

Fig. 2 shows a D-shaped optical fiber (transverse section) in tangential contact with a fiber-ring circumferential-mode optical resonator.

Figs. 3A and 3B show side and top views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 3C and 3D show transverse-sectional views of an adjacent fiber segment and a waveguide fiber segment, respectively, of a fiber-optic waveguide according to the present invention.

Fig. 3E shows a longitudinal-sectional view of a fiber-optic waveguide according to the present invention.

Fig. 4A illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

Figs 4B and 4C show transverse sectional views of an adjacent fiber segment and a waveguide fiber segment, respectively, of a coated optical fiber after laser machining but prior to etching, according to the method for fabrication shown in Fig. 4A.

Fig. 5 illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

Figs. 6A and 6B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 7A and 7B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 8A and 8B show sectional views of a fiber-optic waveguide coupled to a fiber-ring circumferential-mode optical resonator according to the present invention.

Figs. 9A and 9B show sectional views of a fiber-optic waveguide coupled to a "thumbtack" circumferential-mode optical resonator according to the present invention.

Figs. 10A and 10B show longitudinal- and transverse-sectional views, respectively, of a fiber-optic waveguide according to the present invention.

Figs. 11A, 11B, and 11C show a fiber-optic waveguide having passive alignment structures and being coupled to a fiber-ring resonator according to the present invention.

Fig. 12 illustrates a method for coupling a fiber-ring circumferential-mode optical resonator and a fiber-optic waveguide on an alignment substrate according to the present invention.

Figs. 13A and 13B show sectional views of a fiber-ring circumferential-mode optical resonator coupled to a fiber-optic waveguide on an alignment substrate according to the present invention.

Figs. 14A and 14B show sectional views of a fiber-ring circumferential-mode optical resonator coupled to a fiber-optic waveguide and sealed within an alignment substrate according to the present invention.

Figs. 15A and 15B show sectional views of a fiber-ring circumferential-mode optical resonator coupled to two fiber-optic waveguides and sealed within an alignment device according to the present invention.

Figs. 16A, 16B, and 16C show sectional and top views of a micro-sphere circumferential-mode optical resonator coupled to a fiber-optic waveguide and sealed within an alignment substrate according to the present invention.

Fig. 17 illustrates a method for fabricating a fiber-optic waveguide according to the present invention.

It should be noted that the relative proportions of various structures shown in the Figures may be distorted to more clearly illustrate the present invention. In particular, the size differential and resonator thickness may be greatly exaggerated relative to the underlying optical fiber diameter in the Figures for clarity. Various metal, semiconductor, and/or other thin films and/or coatings are also shown having exaggerated thickness for clarity. The text and incorporated references should be relied on for the appropriate dimensions of structures shown herein.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

For purposes of the present written description and/or claims, "circumferential-mode optical resonator" (equivalently, CMOR, CM optical resonator, CM resonator, CMR) shall denote a resonator structure capable of supporting a substantially resonant circumferential optical mode (equivalently, RCOM). The circumferential optical mode may typically have an evanescent portion extending beyond the circumferential-mode optical resonator and may typically be substantially confined near an outer circumferential surface of the resonator (near being defined here as within several microns for visible, near-, or mid-infrared circumferential optical modes). Such a resonator has been/is also often referred to as a whispering-gallery-mode optical resonator (equivalently, WGM optical resonator). Such resonator structures may include, but are not limited to, spheres, near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A8), ring or other closed waveguides, and/or functional equivalents thereof. In particular, the various circumferential-mode optical resonator structures as disclosed in earlier-cited applications A5 and A9-A12 (denoted collectively as "fiber-rings", fiber-ring resonator, or FRR's) are particularly noted for inclusion as circumferential-mode optical resonators for purposes of this disclosure. However, other resonator structures may be equivalently employed without departing from inventive concepts disclose and/or claimed herein. Any resonator having an evanescent portion of a resonant optical mode or that may otherwise be "transversely optically coupled" to another optical element (see definition hereinbelow) may be employed as the resonant optical resonator element of the present invention (i.e., the element that confers wavelength specificity on the optical power control device). Optical resonator structures disclosed in earlier-cited application A8 are particularly noted for inclusion as optical resonators suitable for use in the present invention. Although the term "circumferential-mode optical resonator" is used throughout the remainder of the present disclosure, it should be understood that any optical resonator that may be transversely optically coupled to a transmission waveguide and/or to an optical modulator as disclosed herein shall be considered functionally equivalent to a circumferential-mode optical resonator.

It should also be noted that the terms "optical resonator", "circumferential-mode optical resonator", and so forth shall encompass both single optical resonators as well as coupled systems of multiple optical resonators, unless a single- or multiple-resonator device is specifically designated in the text.

For purposes of the present written description and/or claims, "transmission fiber-optic waveguide" (equivalently, transmission waveguide, transmission fiber-optic, transmission optical fiber, TFOWG, TWG) shall denote an optical fiber (polarization-maintaining or otherwise) provided with a transverse-optical-coupling segment where a portion of a propagating optical mode may extend beyond the fiber-optic waveguide and overlap a portion of some other optical mode, thereby enabling transverse optical coupling between the transmission optical waveguide and another optical element. Such a transmission optical waveguide may comprise an optical fiber taper, a D-shaped optical fiber, an optical fiber with a saddle-shaped concavity in the cladding layer, an optical fiber with a side-polished flattened portion, and/or functional equivalents. Such transmission optical waveguides are described in further detail in earlier-cited applications A1 through A6. Such transmission fiber-optic waveguides typically serve to facilitate insertion of optical power control devices according to the present invention into an optical power transmission system.

For purposes of the written description and/or claims, "transverse optical coupling" (also referred to as "evanescent optical coupling") shall generally denote those situations in which two optical elements, each capable of supporting a propagating and/or resonant optical mode, are optically coupled by at least partial spatial overlap of at least a portion of one optical mode with at least a portion of the other optical mode. The amount, strength, level, or degree of optical power transfer from one optical element to the other through such transverse optical coupling depends on the spatial extent of the overlap (both transverse and longitudinal), the spectral properties of the respective optical modes, and the relative spatial phase matching of the respective optical modes (also referred to as modal index matching; discussed in detail in applications A9-A12).

By controlling the phase mismatch and/or transverse spatial overlap between optical modes, these characteristics may be exploited for controlling optical power transfer between optical elements. For example, by altering the phase mismatch, a device may be switched from a first condition, in which a certain fraction of optical power is transferred

from a first optical mode in a first optical element to a second optical mode in a second optical element (phase mismatch set so that the effective interaction length is about half of the characteristic spatial period described above), to a second condition in which little or no optical power is transferred (phase mismatch set so that the effective interaction length is about equal to the characteristic spatial period). Further discussion of optical coupling may be found in Fundamentals of Photonics by B. E. A. Saleh and M. C. Teich (Wiley, New York, 1991), hereby incorporated by reference in its entirety as if fully set forth herein. Particular attention is called to Chapters 7 and 18.

It should be noted that optical power control devices, their fabrication, and their use according to the present invention are intended primarily for modulating and/or routing propagating optical signals having a wavelength between about 0.8 μm and about 1.7 μm (the wavelength range typically utilized for fiber-optic telecommunications). However, these devices, methods of fabrication, and methods of use may be adapted for use at any desired wavelength while remaining within the scope of inventive concepts disclosed and/or claimed herein.

A waveguide optical fiber for transmitting an optical signal (alternatively, a propagating optical mode) to be controlled, modulated, and/or routed is provided with an transverse-optical-coupling fiber segment 302 between longitudinally adjacent fiber segments 312, as shown generally in Figs. 3A, 3B, 3C, 3D, and 3E. Each of the transverse-optical-coupling fiber and adjacent fiber segments 302/312 comprises a core 304/314 and a cladding layer 306/316, with the respective cores forming a substantially continuous core of fiber-optic waveguide 300 and enabling propagation of an optical mode therethrough. The cladding layers 316 of the adjacent fiber segments 312 are sufficiently large to transversely substantially encompass the propagating optical mode within the cladding layers. The cladding layer 306 of the transverse-optical-coupling fiber segment 302 is asymmetrically disposed about the core 304 thereof and forms a coupling portion 308 of the cladding layer surface. An evanescent portion of the propagating optical mode extends transversely beyond the coupling portion 308 of the cladding layer surface of the transverse-optical-coupling segment 302, thereby enabling transverse optical coupling to other optical devices/structures, as further described hereinbelow and in the patent applications cited and incorporated by reference hereinabove. The transverse optical coupling thus achieved in turn enables control, modulation, and/or routing of the optical mode propagating through the fiber-optic waveguide 300. The asymmetric distribution of

the cladding layer 306 about the core 304 of the transverse-optical-coupling fiber segment 302 may typically be achieved by spatially selective removal of cladding layer material from the transverse-optical-coupling fiber segment.

Single mode optical fiber, including polarization-maintaining (PM) optical fiber, is commonly available commercially having a diameter of about 80 μm or about 125 μm (higher refractive index core plus lower refractive index cladding, excluding any additional jacket material) and a core diameter on the order of about 5 to 10 μm. PM fiber may also include longitudinally extending stressor elements disposed in substantially opposing positions about the core within the cladding layer as shown in Fig.1. Other fiber cladding and core diameters suitable for transmitting the propagating optical mode may be used as well. Spatially-selective and circumferentially asymmetric removal of cladding layer material from an transverse-optical-coupling fiber segment of an optical fiber (PM or otherwise) yields a fiber-optic waveguide for transverse optical coupling according to the present invention. Techniques employed herein may be referred to collectively as cylindrical processing. Such material removal may preferably be achieved by spatially-selective and circumferentially asymmetric etching of the cladding layer of the optical fiber (i.e., “side etching”).

A preferred method for removing cladding layer material from the transverse-optical-coupling fiber segment is illustrated generally in Figs. 4A, 4B, and 4C, and comprises the steps of: 1) providing the adjacent fiber segments 312 and a portion of the length and circumference of the transverse-optical-coupling fiber segment 302 with a mask (shown as stippled shading in Fig. 4A); and 2) spatially-selectively etching the exposed portions of the transverse-optical-coupling fiber segment 302, thereby yielding an asymmetrically disposed cladding layer 306 about the core 304 and providing a coupling portion 308 of the cladding layer surface. The mask may be removed after etching. This procedure may be contrasted to the methods disclosed in prior provisional Application No. 60/183,499, cited hereinabove, wherein complete (360°) cylindrical rings are machined or otherwise provided in the optical fiber outer coating, resulting in substantially circumferentially symmetric removal of cladding layer material and fabrication of fiber rings. Many optical fibers are supplied with an outer coating comprising a polymer jacket (acrylate, polyimide, or the like), and this jacket may be used as a mask provided it adheres sufficiently to the optical fiber during etching. A preferred mask may comprise a carbon outer fiber coating. Optical fiber having a hermetic carbon outer coating (with or

without a polymer jacket over the hermetic carbon coating) may be obtained commercially (Hermeticoat optical fiber, sold by Spectran Specialty Optics) or may be fabricated by deposition of a carbon layer on the fiber cladding (see for example U.S. Patent No. 5,281,247, said patent being hereby incorporated by reference in its entirety as if fully set forth herein). A carbon coating has been found to adhere well to the optical fiber during etching of the optical fiber. Alternatively, the optical fiber may be coated with photo-resist material as the outer fiber coating. A metal coating may also be employed, and whatever type of coating is used, it may first be deposited on the fiber.

Whether the outer coating comprises a polymer jacket, a carbon film, or a photo-resist, the outer coating must be spatially altered appropriately, thereby yielding a mask portion 319 substantially covering the adjacent fiber segments 312 and a mask portion 309 covering the desired portions of the transverse-optical-coupling fiber segment 302 during etching. The mask may preferably be produced by spatially selective laser machining or laser processing of the outer coating, removing the outer coating only from the desired portions of the length and circumference of the transverse-optical-coupling fiber segment. A polymer jacket outer coating may be laser machined using a UV-emitting excimer laser. A carbon film outer coating may be laser machined using a pulsed laser (presumably ablatively) or with a substantially continuous laser (presumably thermally). A photo-resist outer coating may be patterned with a pulsed or continuous laser and processed to remove the outer coating. The techniques disclosed herein may be referred to collectively as "cylindrical processing" (such cylindrical processing techniques are also disclosed in U.S. provisional Application No. 60/183,499, cited hereinabove). During laser machining to produce the mask the optical fiber may be partially rotated about its long axis to produce a partial-ring-like mask pattern 309 on the fiber, extending less than 360° around the circumference of the transverse-optical-coupling fiber segment. Alternatively, the optical fiber may be fully rotated at a substantially uniform angular velocity while the machining laser is modulated so as to remove the outer fiber coating from only a partial ring portion around the circumference of transverse-optical-coupling fiber segment 302, leaving mask pattern 309 extending only partially around fiber segment 302. The machining laser may be modulated in any suitable way, including as examples but not limited to: acousto-optic modulation, electro-optic modulation, mechanical shuttering, modulation of the machining laser pump source, photo-elastic modulation, functional equivalents thereof, and/or combinations thereof. The modulation of the machining laser may be timed to and/or

synchronized with the rotation of the optical fiber in any suitable manner, including as examples but not limited to: direct mechanical coupling, optical-interrupts, electronic timing circuitry, functional equivalents thereof, and/or combinations thereof.

It should be particularly noted that the cylindrical processing techniques as disclosed herein may be coupled with any suitable technique for rotational alignment of a polarization-maintaining (PM) optical fiber, so that partial-ring-like mask pattern 309 may be positioned on the surface of transverse-optical-coupling fiber segment 302 in a predetermined spatial relationship with respect to a polarization axis of the PM fiber. An example of such a rotational alignment technique is the POL technique (Polarization Observation by Lens effect tracing), although other techniques may be equivalently employed. After etching, coupling portion 308 of the surface of transverse-optical-coupling fiber segment 302 will also be positioned in a similarly predetermined spatial relationship with respect to the polarization axis of the PM fiber. This in turn insures that the polarization state of the propagating optical mode is well-defined and reproducible at the point in the fiber-optic waveguide where the transverse optical coupling occurs. Any alignment feedback signal generated by the rotational alignment technique (such as the POL technique) may also be employed as a timing/synchronization signal for modulation of the machining laser with respect to rotation of the optical fiber, as disclosed in the preceding paragraph.

Rotation during laser machining should preferably be substantially concentric (thereby substantially minimizing any "orbital" motion of the fiber cross-section about the rotation axis, also referred to as centration error). This may preferably be achieved by using a rotational guide such as a vacuum V-block for defining a fiber rotation axis. Sufficient negative pressure may be applied to maintain low centration error during rotation, but must be sufficiently low to allow smooth rotation at a sufficiently high speed (typically 100-300 rpm). Paired V-blocks may be employed, one on each side of the fiber length to be machined, to enhance the positioning stability of the rotating fiber. Alternatively, a capillary tube or fiber ferrule (singly or in pairs) may be used in any equivalent manner to align the fiber for rotation and laser machining. (Hereinafter, use of a capillary for fiber alignment as described herein shall be understood to equivalently encompass use of a fiber ferrule). A capillary tube should be chosen having an inner diameter closely matching the optical fiber diameter. For example, the carbon-coated fiber mentioned hereinabove has a nominal diameter of 125 μm. Capillary tubing is

commercially available (0.4 lambda supplied by Drummond Scientific, Inc.) having an inner diameter of 126.4±0.3 μm, making it ideal for concentrically aligning and rotating the fiber during laser machining. This V-block, capillary or fiber ferrule alignment technique for substantially concentric rotation of the optical fiber may be employed during any other fabrication step requiring such rotation of the optical fiber, as set forth hereinbelow. Similar use of a capillary for substantially concentric rotation of an optical fiber during laser processing is described in a publication of Presby et al. (Applied Optics, Vol 29, 2692 (1990)), said publication being hereby incorporated by reference in its entirety as if fully set forth herein. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable means may be employed for substantially concentric rotation of the optical fiber during laser machining, including but not limited to V-blocks, a capillary tube, a fiber ferrule, an alignment chuck, an alignment jig, an indexed fiber holder, and so forth, either singly or in pairs. Alternatively, a spindle (air-bearing or otherwise), stepper-motor-driven rotators, servo-motor-driven rotators, encoder, or other rotator may be equivalently employed for rotating the optical fiber during laser machining without a capillary, provided the rotation of the rotator is substantially concentric (i.e., little or no orbital motion of the rotator during rotation) and if the optical fiber can be mounted substantially concentrically with the rotation axis of the rotator.

In a preferred method for precisely machining rings in a hermetic carbon mask material, the carbon coated fiber may be threaded through a first V-block, capillary tube or other rotation guide. A relatively long segment of the carbon coated fiber (as long as several inches or more) may extend from the first end of the capillary, and is coupled to a rotation device. The rotation device must produce controlled, substantially uniform rotary motion of the fiber with minimal thrust error. (The term "thrust error" refers to any unwanted longitudinal motion that may accompany the desired rotary motion. The thrust error that is synchronous with the rotation results in a tilt of the machined ring with respect to a plane perpendicular to the fiber axis, an effect which may be used to intentionally produce tilted rings. A prototype system (Fig. 5) has been successfully constructed using a precision drill press (Cameron Micro Drill), but a preferred embodiment, also successfully prototyped, comprises an air bearing spindle 400 (Professional Instruments 4B) belt-driven by a stepper motor/encoder system (not shown). An air-bearing spindle may be preferred as having the smallest achievable thrust error currently available

commercially (as small as 25 nm; thrust error of about 1 μm or less is generally sufficient for the present invention; thrust error as high as 10 μm may be tolerated under less demanding circumstances). Carbon coated fiber 402 may be secured substantially co-axially to the air bearing spindle (optionally cemented within a capillary tube 404 and the capillary tube secured to air bearing spindle 400). Without departing from inventive concepts disclosed and/or claimed herein, other devices may be equivalently employed to produce the desired rotary motion, including but not limited to rotation stages, stepper-motor-driven rotators, servo-motor-driven rotators, and the like. As the air-bearing spindle or other rotary device rotates the carbon-coated fiber, the fiber rotates within a vacuum V-block, capillary tube, or other rotation guide 408 with low centration error. As long as both fiber and the rotation guide are substantially uncontaminated, this rotation of the fiber within the capillary will not damage the carbon coating. If desired, it may be possible to drive air or other gas through a capillary around the rotating fiber to serve as an air-bearing. The alignment fiber is substantially rigidly mounted in a standard fiber chuck or other similar device 409, and a relatively short segment of the carbon-coated fiber 402 extends beyond the second end of the rotation guide 408. A second rotation guide may be employed on the far end of the fiber to further limit lateral motion during rotation. A microscope objective 410 (60X in the prototype; others may be used as appropriate) for delivering a laser beam for laser machining may be mounted on a precision 3-axis translator 412 for precise positioning relative to the carbon-coated fiber.

A laser beam 414 from an argon ion laser (typically multi-line visible output, mainly 488 nm and 514 nm, between about 10 mW and about 100 mW average power) or a continuous wave frequency-doubled YAG laser (visible output, at 532 nm, between about 10 mW and about 100 mW average power) is brought to a spot size between about 0.2 μm and about 3 μm, preferably about 0.5-1.0 μm, by the objective 410 onto the surface of the fiber 402 as it rotates, thereby removing the carbon coating from the fiber (presumably by a thermal mechanism). A beamsplitter 416 in the laser beam path allows back-scattered and/or back-reflected laser light from the fiber to be imaged at 418 in order to adjust the focus of the laser beam sufficiently precisely relative to the surface of the fiber. The laser beam need not necessarily be focused at the surface of the fiber (although it could be, if desired). Use of a microscope objective is important for several reasons. The highly convergent beam enables the machining of rings in the hermetic carbon coating as small as 0.5 to 3 μm wide with relatively sharp edges, which in turn reduces the

roughness of the edges of the resonator segment produced by subsequent etching. A tight focus on the machined surface of the fiber also insures that the laser beam transmitted through the fiber will be sufficiently defocused when it reaches the opposite surface of the fiber so that none of the coating will be removed from the opposing surface. The centration error of the carbon-coated fiber within the capillary tube is typically sub-micron, well within the depth-of-focus of the tightly focused laser beam (typically a few microns). It has also been observed that microscopic defects may occur in the portions of the carbon coating left behind after laser machining, resulting in unwanted etched spots and edge roughness in the resonator fiber segment and degradation of optical performance. This effect is believed to be due to excessive heating of the carbon-coated fiber during laser exposure, which causes damage to the carbon coating and/or the underlying silica adjacent to the carbon being exposed. In addition, exposure of the carbon-coated fiber at high power (greater than about 30 mW) causes texturing of the silica underlying the exposed carbon, presumably due to melting of the underlying silica. It has been observed that reducing the optical power of the exposing laser beam to 10-25 mW substantially eliminates the thermal damage problem as well as the surface texturing problem. It has also been observed that flowing gas (O_2, N_2, and ambient air have been used successfully, although O_2 may be preferable) around the fiber as it is machined seems to mitigate the defect problem.

It should be noted that a microscope objective may not be required for sufficiently precise machining of partial rings in the carbon coating. In general, if the optical fiber is substantially transparent to the wavelength used for machining the carbon coating (or other fiber outer coating), then the beam must be highly convergent (with an objective or similar optical assembly having an NA greater than about 0.3, preferably around 1) so that the transmitted beam is too large to damage the fiber outer coating on the opposite side of the fiber. However, if the fiber is not transparent to the laser-machining wavelength (157 nm from an F_2 excimer laser, for example, or if the fiber is a hollow fiber filled with material non-transparent at the laser-machining wavelength, or if the fiber is doped to render it non-transparent at the laser-machining wavelength), then damage to the opposite side of the fiber is no longer an issue, and the optical assemblies having longer working distances (i.e., smaller NA) may be employed. This is a general principle that may be applicable to other laser-machining steps set forth hereinbelow. Any laser source suitable for laser machining (known in the art or hereafter developed) may be employed while

remaining within the scope of inventive concepts disclosed and/or claimed herein, for any laser machining step disclosed herein.

Alternatively, a suitable partial-ring etch mask may be provided for the transverse-optical-coupling segment by spatially-selective deposition of an outer fiber coating (i.e., mask material) on the adjacent fiber segment and desired portions of the transverse-optical-coupling segment, leaving partial (less than 360°) rings of cladding layer surface exposed. Masks may be provided in this way by spatially-selective deposition of an outer fiber coating, which may preferably comprise a metal coating or other suitable coating material. Shadow masking techniques may be employed to achieve spatially-selective deposition of mask material, or the fiber may be positioned within a groove on a substrate prior to deposition of the mask material.

For silica or silicate-based optical fibers, aqueous hydrofluoric acid (HF) is an effective etching agent for spatially-selective removal of material from the desired portions of the length and circumference of the transverse-optical-coupling fiber segment of the fiber-optic waveguide after providing a suitable mask. The amount of material removed can be precisely controlled by controlling the etching time, etchant concentration and/or pH, and/or temperature. The etched surfaces are substantially smooth and substantially free of irregularities, thereby minimizing optical scatter from the etched surfaces of the fiber-optic waveguide. The concentration of HF used to etch the optical fiber may be between about 5% and about 50% HF buffered with NH_4F, should preferably be between about 7% and about 8% HF and between about 30% and about 40% NH_4F, and most preferably about 7.2% HF and 36% NH_4F. The most preferred concentration yields an etch rate of about 80 nm/min, and is available commercially (Transene Company, Inc.). Another suitable HF concentration is 1 part 40% HF(aq) combined with 10 parts 40% NH_4F(aq), as disclosed in the publication of Eisenstein et al. (Applied Optics, Vol 21, 3470 (1981)), said publication being incorporated by reference in its entirety as if fully set forth herein. Any of these disclosed concentrations may be employed during any other fabrication step requiring an HF etch, as set forth hereinbelow. While remaining within the scope of inventive concepts disclosed and/or claimed herein, any suitable wet or chemical etching agent (either known in the art or hereafter developed) may be used to reduce the diameter of the adjacent fiber segments or other portions of the fiber. Alternatively, dry or reactive ion etching procedures, employing suitable etch masks (metal masks or polymer masks, for example), may be used to reduce the diameter of the

adjacent fiber segments or other portions of the fiber. After etching, the mask may be removed (if desired) by any of a variety of methods, including but not limited to non-spatially-selective laser machining, chemical/solvent removal, thermal removal (i.e., burning), exposure to an electrical discharge, plasma ashing, ion sputtering, and other suitable methods for removing the mask (known in the art or hereafter developed).

It should be noted that as the etching process proceeds radially inward from the laser-machined partial rings (i.e., the "un-masked" portion of the surface of the transverse-optical-coupling fiber segment 302), transverse edges of the transverse-optical-coupling fiber segment become exposed to the etchant and come under attack. The resulting coupling portion 308 of the cladding layer surface of the transverse-optical-coupling fiber segment 302 therefore often acquires a saddle-like shape, having a concave longitudinal-sectional shape (Fig. 3E) near at least a portion of the core 304 of the transverse-optical-coupling fiber segment 302 and a convex transverse-sectional profile (Fig. 3D) near at least a portion of the core 304 of the transverse-optical-coupling fiber segment 302. The precise shapes and radii-of-curvature of these (not necessarily circularly arcuate) sectional profiles may be controlled by the size (width and circumferential extent) and/or shape of the outer fiber coating (mask material 309/319) removed during the mask-providing step, and by controlling the etching time, etchant concentration and/or pH, and/or temperature. For example, a wider partial ring of removed mask material would result in a more shallow longitudinal section (larger concave radius of curvature). A partial ring of removed mask material having a larger circumferential extent would yield a sharper transverse section (smaller convex radius of curvature). For a given combination of optical fiber type/material and etchant, some experimentation is required to correlate mask size/shape, etching time and/or conditions, and the details of the shape of the resulting coupling portion 308 of the surface of the cladding layer 306 of the transverse-optical-coupling fiber segment 302. Once these correlations are established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

By reducing the circumferential extent of the "unmasked" portion of the surface of transverse-optical-coupling fiber segment 302, the convex transverse sectional profile of coupling portion 308 may be made less sharply curved, or even substantially flat (Figs. 6A and 6B). This may offer the advantages of D-shaped fiber as disclosed hereinabove, without the attendant difficulties of splicing D-shaped optical fiber to standard,

substantially circular-cross-sectioned single-mode optical fiber (PM or otherwise). Further reducing the circumferential extent of the "unmasked" portion of the transverse-optical-coupling fiber segment (for example resulting in essentially a longitudinal slit-like "unmasked" portion of the surface of transverse-optical-coupling fiber segment 302) may result (after etching) in coupling portion 308 of the cladding layer surface acquiring a scooped, or pit-like, shape having concave profiles in both longitudinal and transverse sections (Figs. 7A and 7B).

Another method for tailoring the shape of coupling portion 308 comprises machining of multiple partial rings on transverse-optical-coupling fiber segment 302, leaving an intervening ring of outer fiber coating material between each pair of adjacent partial rings (Fig. 17). The intervening rings are sufficiently narrow so that upon etching of the cladding layer 306, the multiple etched surfaces (each resulting from one of the machined partial rings) coalesce into a single coupling portion 308 of transverse-optical-coupling fiber segment 302. Coupling portion 308 may initially be rough, but further etching after the partial rings coalesce results in a substantially smooth cladding layer surface. By tailoring the number, widths, spacings, and circumferential extents of each of the multiple partial rings (independently; they need not all be the same), virtually any desired shape for coupling portion 308 may be achieved. For a given combination of optical fiber type/material and etchant, some experimentation is required to correlate the number, widths, spacings, and circumferential extents of each of the multiple partial rings, etching time and/or conditions, and the details of the shape of the resulting coupling portion 308 of the surface of the cladding layer 306 of the transverse-optical-coupling fiber segment 302. Once these correlations are established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

The fiber-optic waveguide thus fabricated is more robust than a fiber taper. The cladding layer remaining on the transverse-optical-coupling fiber segment transversely opposite the coupling portion of the cladding layer surface may be several tens of microns thick, in contrast to the 1-5 μm total thickness of a typical fiber taper. The overall length of the coupling portion may be as small as about a hundred microns long, whereas a typical tapered segment of an optical fiber taper may be substantially longer, and therefore less mechanically stable, rigid, and/or robust. The fiber-optic waveguide according to the present invention is therefore a substantially sturdier structure, able to withstand manipulation without excessive breakage and to maintain alignment once secured to an

alignment structure. Furthermore, fiber tapers are often capable of supporting many different propagating optical modes, complicating the use of such fiber tapers for coupling to single circumferential optical modes of a circumferential-mode optical resonator. A fiber-optic waveguide fabricated according to the present invention, however, typically retains the single-mode characteristics of the fiber from which it was fabricated. Fiber-optic waveguides according to the present invention may be fabricated from polarization-maintaining (PM) optical fiber, thereby enabling polarization-specific propagation of an optical mode through the waveguide as well as polarization-specific transverse optical coupling to the circumferential-mode optical resonator.

A saddle-like shape of the coupling surface of the transverse-optical-coupling fiber segment may be tailored to facilitate subsequent use of the fiber-optic waveguide for transverse optical coupling to a circumferential-mode optical resonator, as illustrated in Figs. 8A and 8B. For example, such circumferential-mode optical resonators may take the form of fiber-rings (as disclosed in applications A5 and A9-A12, cited hereinabove), micro-spheres, micro-disks (including structures such as a "thumbtack" fabricated on a substrate, wafer, or chip; described in earlier-cited publication P7 and disclosed in U.S. Patent No. 5,343,490, said patent being hereby incorporated by reference as if fully set forth herein), and/or micro-rings (including structures such as a "ring mesa" fabricated on a substrate, wafer, or chip) which must be brought into substantial tangential engagement with the coupling portion of the surface of the cladding layer of the transverse-optical-coupling fiber segment. The concave radius of curvature of the longitudinal-sectional shape of saddle-shaped coupling portion 308 of the cladding layer surface should preferably be at least about as large as the radius of the circumferential-mode optical resonator 602, thereby enabling reliable, reproducible, and stable optical coupling between a circumferential optical mode of the resonator 602 and the propagating optical mode in the transverse-optical-coupling fiber segment 302. The concave radius of curvature of the longitudinal-sectional shape may also determine the degree of transverse optical coupling between the propagating optical mode in the fiber-optic waveguide 302 and the circumferential optical mode of the circumferential-mode optical resonator 602. Reliable, reproducible, and stable transverse optical coupling between the fiber-optic waveguide and a circumferential-mode resonator may be further enabled by the transverse-sectional shape of the coupling portion 308 of the cladding layer 306. In particular, for a fiber-ring circumferential-mode optical resonator as disclosed in Application No. 60/183,499 (cited

and incorporated by reference hereinabove), a substantially flat or convex transverse sectional profile for coupling portion 308 is necessary (Figs. 8A and 8B). For a micro-sphere circumferential-mode optical resonator, however, a concave transverse sectional profile for coupling portion 308 may be more suitable for enabling reliable, stable, and reproducible transverse optical coupling. For a "thumbtack" micro-disk circumferential-mode resonator fabricated on a substrate, a longitudinally elongated coupling portion 308 having both transverse and longitudinal sectional profiles convex may be most suitable for enabling reliable, stable, and reproducible transverse optical coupling (Figs. 9A and 9B). It should be noted that whatever methods/techniques may be employed for asymmetric removal of cladding layer material from the transverse-optical-coupling fiber segment (disclosed herein or otherwise), the shape of the resulting coupling portion of the cladding surface may be controlled in the manner and for the purposes as stated hereinabove.

In order to achieve transverse optical coupling between the fiber-optic waveguide 300 and a circumferential-mode optical resonator 602, at least a portion of the core 304 of the transverse-optical-coupling fiber segment 302 must be sufficiently near the coupling potion 308 of the surface of the cladding layer 306 thereof, thereby enabling an evanescent portion of the propagating optical mode to extend transversely beyond the coupling portion 308 of the cladding layer surface. The thickness of cladding layer material remaining between the core 304 and the coupling portion 308 of the cladding layer surface may preferably be between about 0 μm (exposed core) and about 10 μm, although the thickness may be as large as about 30 μm. Since the doped core of many optical fibers etches more slowly than the cladding layer, the coupling portion 308 of the cladding layer surface may be etched away leaving a protruding "ridge" waveguide comprising the exposed core 304, as shown in Figs. 10A and 10B. As with the shape of the coupling portion 308 of the cladding layer surface, experimentation may be required to establish correlations between mask size/shape, etching time and/or conditions, and the resulting thickness of cladding layer material 306 remaining over the core 304 for a given combination of optical fiber type/material and etchant. Once these correlations are established, they may be used to reliably and reproducibly produce fiber-optic waveguides according to the present invention.

Another technique for controlling the removal of cladding layer material comprises the step of monitoring the optical loss of the fiber-optic waveguide 300 as cladding material 306 is removed. As the coupling portion 308 of the cladding layer surface moves

closer to the core 304 of the transverse-optical-coupling fiber segment 302, optical loss from the cladding layer surface increases, thereby decreasing the throughput of the fiber-optic waveguide 300. By terminating the etching step in response to the optical loss reaching some pre-determined level, the coupling portion 308 of the cladding layer surface may reproducibly be brought to within a specified distance of the core 304. Target levels for the optical loss of the fiber-optic waveguide range between about 0.1 dB and about 30 dB, preferably between about 0.1 dB and about 10 dB, and most preferably between about 0.1 dB and about 3 dB. Experimentation may be required to establish correlations between measured optical loss and the corresponding thickness of cladding layer material remaining over the core. The ranges for the pre-determined loss level may be measured with the fiber-optic waveguide is immersed in the etchant, or removed from the etchant (with or without being cleaned and/or dried).

In order to more readily achieve and maintain reliable, reproducible, and stable optical coupling between a circumferential-mode optical resonator 602 (particularly a fiber-ring circumferential-mode optical resonator as disclosed in applications A5 and A9-A12, cited hereinabove) and a fiber-optic-waveguide 300 according to the present invention, the fiber-optic waveguide 300 may be fabricated from polarization-maintaining (PM) optical fiber. Panda-type PM optical fiber (Fig. 1) may preferably be used to fabricate a fiber-optic waveguide using mask-and-etch methods according to the present invention. The stressor elements of the PM fiber, like the core, generally etch at a slower rate than the surrounding cladding layer material. After masking and etching according to the techniques disclosed herein, longitudinally extending passive alignment structures 305 result which extend transversely from the coupling portion 308 of the cladding layer surface of the transverse-optical-coupling fiber segment 302 (Fig. 11A). These passive alignment structures 305 are positioned in a predetermined spatial relationship with respect to the polarization axis of the PM optical-fiber as disclosed hereinabove, and may therefore be particularly well-suited for achieving and maintaining reliable, reproducible, stable, and polarization-specific optical coupling between the fiber-optic waveguide 300 and a fiber-ring circumferential-mode optical resonator 602, as shown in Figs. 11B and 11C. The fiber-ring circumferential-mode resonator 602 may be provided with suitable mating mechanical indexing structures 606 on adjacent fiber segments 604 for further facilitating reliable, reproducible, and stable optical coupling (Fig. 11B). Contact between

alignment structures 305 and fiber-ring 602 may affect the performance of the embodiment of Fig. 11C.

Without departing from inventive concepts disclosed and/or claimed herein, any suitable methods or techniques (currently extant or hereafter developed) may be employed for asymmetric removal of cladding layer material from the transverse-optical-coupling fiber segment. Such removal of cladding material may be performed subject to constraints, requirements, and controls as described elsewhere herein. Such methods or techniques may include but are not limited to: masking/etching; wet etching; chemical etching; plasma etching; dry etching; ion beam lithography; direct laser machining of cladding layer material; mechanical machining, polishing, lapping, and/or grinding of cladding material; ablative techniques; functional equivalents thereof; and/or combinations thereof. Many suitable methods/techniques are disclosed in applications A5 and A9-A12, cited hereinabove.

In a resonant optical power control device according to the present invention, a circumferential-mode optical resonator is coupled to a fiber-optic waveguide according to the present invention. A propagating optical mode (equivalently, an optical carrier wave) to be controlled propagates through the fiber-optic waveguide where it may be controlled, modulated, and/or routed, either passively or by application of control signals to the control device. The fiber-optic waveguide is adapted (as disclosed hereinabove) to enable transverse optical coupling between the propagating optical mode of the fiber-optic waveguide and a resonant circumferential optical mode of the circumferential-mode optical resonator or other optical resonator and/or waveguide, thereby enabling controlled modulation and/or routing of the propagating optical mode of the fiber-optic waveguide. Such optical power control devices and control, modulation, and/or routing techniques are described in detail in applications A1-A13 cited hereinabove.

In order to achieve and maintain reliable, reproducible, and stable optical coupling between a fiber-optic waveguide and a circumferential-mode resonator during and after manufacture of a resonant optical power control device according to the present invention, an alignment device may be employed (Figs. 12, 13A, 13B, 14A, 14B, 16A, 16B, and 16C). Such an alignment device may comprise a first alignment substrate 502 having a waveguide-alignment groove 506 and a resonator-alignment groove 504 thereon. A method for fabricating a resonant optical power control device according to the present

invention comprises the steps of: 1) positioning and securing a fiber-optic waveguide 300 within the waveguide-alignment groove 506; and 2) positioning and securing the circumferential-mode optical resonator (for example a fiber-ring circumferential-mode resonator 602 as disclosed in provisional Application No. 60/183,499, a micro-sphere, or of some other functionally equivalent configuration as enumerated earlier herein) within the resonator-alignment groove 504. The waveguide-alignment groove 506 and resonator-alignment groove 504 may be positioned on the alignment substrate 502 so that when positioned and secured therein, the fiber-optic waveguide 300 and the fiber-ring circumferential-mode resonator 602 are in substantial tangential engagement (typically mechanical contact between the coupling portion 308 of the cladding layer surface of the transverse-optical-coupling fiber segment 302 and the circumference of the resonator 602; see below and Figs. 8A, 8B, 13A, 13B, 14A, and 14B), thereby optically coupling the circumferential-mode resonator 602 to the fiber-optic waveguide 300. Optical coupling between the circumferential-mode resonator 602 and the fiber-optic waveguide 300 may be achieved as long as at least portions of each of the circumferential optical mode of the resonator and the propagating optical mode of the fiber are spatially overlapped. The degree of overlap and the degree of phase matching determines the degree of optical coupling between the resonator and the fiber. Actual mechanical contact is not required, only that the resonator and waveguide be sufficiently close to permit the overlap. However, in a preferred embodiment of an optical power control device according to the present invention, optical coupling between the resonator and the waveguide is most reproducibly, reliably, and stably achieved by positioning and securing the circumferential-mode resonator 602 and the fiber-optic waveguide 300 in mechanical contact with one another within each respective alignment groove. Figs. 16A, 16B, and 16C show a similar configuration of a fiber-optic waveguide 300 and a circumferential-mode micro-sphere resonator 620 connected to a tapered end 632 of an optical fiber 624.

As shown in Fig. 12, the resonator-alignment groove and the waveguide-alignment groove may preferably be substantially perpendicular, so that the waveguide 300 and circumferential-mode fiber-ring resonator 602 may be substantially co-planar. Similarly, substantially perpendicular alignment grooves insure that a circumferential-mode micro-sphere resonator would be aligned with its symmetry axis substantially perpendicular to fiber-optic waveguide 300 (Figs. 16A and 16B; it should be noted the such "micro-spheres" are typically slightly oblate, with a symmetry axis substantially coinciding with

the tapered fiber end). The alignment grooves may have substantially constant width and depth profiles along their respective lengths, or alternatively may have tailored width and/or depth profiles. The cross-sectional shape of the alignment grooves may preferably be substantially rectangular (in fact generally slightly trapezoidal due to laser machining or other etch processes typically employed), but may alternatively have any suitable cross-sectional shape for positioning and securing the circumferential-mode resonator and the fiber-optic waveguide. The depths of the resonator-alignment groove and waveguide-alignment groove are preferably chosen so that when positioned and secured therein, the waveguide and circumferential-mode resonator are in direct contact and therefore optically coupled in a reproducible, reliable, and stable manner (Figs. 13A, 13B, 14A, 14B, 16A, and 16B). The depths chosen depend on the mechanical configurations of the circumferential-mode resonator and the fiber-optic waveguide, as may be readily determined for a particular configuration by one skilled in the art. Either the waveguide-alignment groove or the resonator-alignment groove may be the deeper groove, and typically the component (waveguide or resonator) corresponding to the deeper groove is positioned and secured in its respective groove first, and the other component positioned and secured afterward, although this need not always be the case. If multiple circumferential-mode resonators are to be coupled to a single fiber-optic waveguide through multiple transverse coupling surfaces, the multiple circumferential-mode resonators may be positioned in alternating positions above and below the fiber-optic waveguide, thereby enhancing the overall mechanical stability of the assembly (not shown). Any of a variety of functionally equivalent methods may be employed for securing the fiber-optic waveguide and/or the circumferential-mode resonator within the respective alignment groove, including but not limited to: application of adhesives, epoxies, resins, polymers, solders, and the like; welding or fusing; and providing a mechanical retainer for retaining the fiber-optic waveguide and/or circumferential-mode resonator within the respective alignment groove, such as a clamp, clip, fastener, plate, or other like device. In an alternative embodiment of an optical power control device, the fiber-optic waveguide may be fused or welded (with a CO_2 laser, for example) to the circumference of a circumferential-mode resonator to insure stable, reliable, and reproducible optical coupling. Once the fiber-optic waveguide and circumferential-mode resonator have each been positioned and secured within the respective alignment groove, the alignment device may be sealed (preferably hermetically sealed) to isolate the fiber

and resonator from the use environment of the optical power control device. This is important for a number of reasons. First, the optical coupling relies on the propagation of evanescent optical waves from free surfaces of the fiber-optic waveguide and circumferential-mode resonator. Any contamination of these free surfaces may drastically alter the optical properties of the waveguide and/or resonator and/or optical coupling thereof, thereby altering the performance of the optical power control device. Similarly, any movement of the fiber-optic waveguide relative to the circumferential-mode resonator may also alter the optical coupling and performance of the control device. The alignment device may comprise a cover, second substrate, or other functionally equivalent component 508 that may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like; or using welding or fusion), leaving the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system (Figs. 13A, 14A, and 16A).

In a preferred embodiment of a optical power control device according to the present invention, a circumferential-mode resonator is employed having been fabricated from an optical fiber as disclosed in applications A5 and A9-A12. Such a circumferential-mode resonator fabricated from an optical fiber and comprising a resonator fiber segment 602 and adjacent fiber segments 604 (i.e., a fiber-ring resonator) may be particularly well-suited for use in the optical power control device fabrication methods described herein. The adjacent fiber segments 604 may serve to reproducibly, reliably, and stably position the circumferential-mode resonator 602 within the resonator-alignment groove 504, particularly in directions substantially orthogonal to the longitudinal axis of the resonator fiber segment 602 and adjacent fiber segments 604. Proper longitudinal positioning is required so that the fiber-optic waveguide 300 tangentially engages the resonator fiber segment 602 and not an adjacent fiber segment 604. This may be most simply accomplished by providing a blind resonator-alignment groove 504, truncating an adjacent fiber segment 604 at an appropriate length, and positioning the circumferential-mode resonator 602 in resonator-alignment groove 504 so that the truncated end of adjacent fiber segment 604 butts up against the blind end of resonator-alignment groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of the fiber may serve to adjust the longitudinal position of the circumferential-mode resonator within resonator-alignment groove 504. Alternatively, alignment structures provided on the adjacent fiber segments 604 may serve to properly longitudinally position the

circumferential-mode resonator 602 within the resonator-alignment groove 504. Preferred alignment structures that may be provided on one or more of the adjacent fiber segments 604 may comprise circumferential grooves and/or circumferential annular flanges for engaging corresponding complimentary alignment structures (flanges and/or grooves, respectively) that may be provided in the resonator-alignment groove 504 of the alignment substrate 502. Such alignment structures are more fully disclosed in provisional Application No. 60/183,499, cited hereinabove. Other suitable alignment structures may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. The fiber-optic waveguide 300 may be precisely transversely positioned by virtue of waveguide-alignment groove 506, while the concave longitudinal-sectional shape of the coupling portion 308 of the cladding layer surface of the transverse-optical-coupling fiber segment 302 may preferably serve to longitudinally position the fiber-optic waveguide 300 within the waveguide-alignment groove 506 with respect to the circumferential-mode resonator 602. Alternatively, fiber-optic waveguide 300 may be provided with alignment structures (grooves, flanges, or the like) on adjacent fiber segments 312 in a manner analogous to that disclosed for the circumferential-mode resonator 602 and adjacent fiber segments 604, and corresponding complimentary structures may be provided in waveguide-alignment groove 506, in order to achieve reliable, reproducible, and/or stable longitudinal, transverse, and/or rotational positioning of fiber-optic waveguide 300.

In an alternative embodiment of a optical power control device according to the present invention, a circumferential-mode micro-sphere resonator is employed having been fabricated from an optical fiber as disclosed in earlier-cited applications A1 through A4. Such a circumferential-mode micro-sphere resonator fabricated from an optical fiber and comprising a micro-sphere resonator 620 connected to a tapered section 622 of an optical fiber 624 may be employed in the optical power control device fabrication methods described herein. The optical fiber 624 may serve to reproducibly, reliably, and stably position the circumferential-mode micro-sphere resonator 620 within the resonator-alignment groove 504, particularly in directions substantially orthogonal to the symmetry axis of the micro-sphere resonator 620. Proper longitudinal positioning is required so that the fiber-optic waveguide 300 tangentially engages the micro-sphere resonator 620. This may be most simply accomplished by providing a blind resonator-alignment groove 504, truncating the optical fiber 624 at an appropriate length, and positioning the

circumferential-mode micro-sphere resonator 620 in resonator-alignment groove 504 so that the truncated end of the optical fiber 624 butts up against the blind end of resonator-alignment groove 504. If the truncated end is angle polished and the blind groove end is angled, rotation of the fiber may serve to adjust the longitudinal position of the circumferential-mode resonator within resonator-alignment groove 504. Alternatively, alignment structures provided on the optical fiber 624 may serve to properly longitudinally position the circumferential-mode micro-sphere resonator 620 within the resonator-alignment groove 504. Preferred alignment structures that may be provided on the optical fiber 624 may comprise circumferential grooves and/or circumferential annular flanges for engaging corresponding complimentary alignment structures (flanges and/or grooves, respectively) that may be provided in the resonator-alignment groove 504 of the alignment substrate 502. Such alignment structures are more fully disclosed in provisional Application No. 60/183,499, cited hereinabove. Other suitable alignment structures may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. The fiber-optic waveguide 300 may be precisely transversely positioned by virtue of waveguide-alignment groove 506, while the concave longitudinal-sectional shape of the coupling portion 308 of the cladding layer surface of the transverse-optical-coupling fiber segment 302 may preferably serve to longitudinally position the fiber-optic waveguide 300 within the waveguide-alignment groove 506 with respect to the circumferential-mode micro-sphere resonator 620. Alternatively, fiber-optic waveguide 300 may be provided with alignment structures (grooves, flanges, or the like) on adjacent fiber segments 312 in a manner analogous to that disclosed for the circumferential-mode resonator 602 and adjacent fiber segments 604 or optical fiber 624, and corresponding complimentary structures may be provided in waveguide-alignment groove 506, in order to achieve reliable, reproducible, and/or stable longitudinal, transverse, and/or rotational positioning of fiber-optic waveguide 300.

A major portion of the cost associated with manufacture of optical power control devices arises from the labor-intensive steps involved in properly aligning the components of the device. Often active alignment techniques are required wherein some measure of device performance (examples include insertion loss, modulation depth, bandwidth, and so forth) is monitored and optimized with respect to alignment of components of the device. Such active alignment steps are reduced or substantially eliminated from fabrication of a resonant optical power control device according to the present invention. For example,

appropriate depths chosen for the resonator-alignment groove and the waveguide-alignment groove, and circumferential grooves and/or annular flanges provided on an adjacent fiber segment or connected optical fiber and appropriately positioned mating structures in the resonator-alignment groove for engaging the grooves/flanges, both serve to enable positioning of the circumferential-mode resonator in substantial tangential engagement (in mechanical contact, for example) with the fiber-optic waveguide when each is positioned within the respective alignment groove, without any need for active monitoring of device properties during assembly and/or alignment. Such passive alignment techniques substantially reduce manufacturing time and cost, and substantially enhance reliability and consistency of the manufactured devices.

Circumferential-mode optical resonators and methods for fabrication thereof have been described in earlier-cited applications A1 through A13 wherein the circumferential-mode resonator (fiber-ring, micro-sphere, or other functionally equivalent resonator structure) may be provided with a modulator for enabling controlled modulation of optical properties of the circumferential-mode resonator. The modulator may be provided in a variety of ways, including but not limited to: in a circumferential-mode resonator fabricated by providing material on the circumference of a resonator fiber segment, the material provided may enable modification of optical properties of the circumferential-mode resonator; in a circumferential-mode resonator fabricated by spatially-selective doping of a resonator fiber segment, the doped material may enable modification of optical properties of the circumferential-mode resonator; a modulator material may be provided on at least a portion of the circumference of the circumferential-mode resonator and therefore be encompassed by an evanescent portion of the circumferential-mode optical wave extending radially from the resonator fiber segment; an adjacent fiber segment may be truncated sufficiently close to the resonator fiber segment so that at least a portion of the resulting fiber end face is encompassed by an evanescent wave portion of the circumferential-mode optical wave extending longitudinally from the resonator fiber segment, and a modulator material may be provided on the portion of the fiber end face thus encompassed; combinations thereof; and/or functional equivalents thereof. The modulator material (including deposited, bonded, attached, and/or doped material) may include but is not limited to: an electro-optic material; an electro-absorptive material; a non-linear optical material; a semi-conductor material (including hetero-structures such as quantum wells); an optical gain medium (a laser material, for example); a piezo-electric

material; combinations thereof; and/or functional equivalents thereof. The modulator may enable controlled modulation of one or more optical properties of the circumferential-mode resonator, including but not limited to: optical gain and/or loss; optical coupling to the circumferential-mode resonator; a resonant frequency of the circumferential-mode resonator; combinations thereof; and/or functional equivalents thereof.

For each of the various modulator structures, methods, and materials recited hereinabove for a circumferential-mode resonator, some sort of control signal must be applied to the modulator. A modulator control element may therefore be provided on the alignment device for providing such signals to a modulator of a circumferential-mode resonator. Such signals may comprise an electronic control signal, an optical control signal, a mechanical control signal, and/or other control signal, and the modulator control element may comprise means for applying such control signals to the modulator. Examples of such means may include, but are not limited to: electrical conductors, wires, cables, electrodes, electrical contacts, ohmic contacts, wireless transmitters and/or receivers, semiconductors, semiconductor hetero-structures (including quantum wells), diodes, triodes, transistors, field-effect transistors (FET's), CMOS devices, integrated circuits, ASIC's, digital circuits, analog circuits, optical fibers, lenses, micro-lenses, mirrors, prisms, integrated optics, adaptive optics, light sources, laser sources, laser diodes, light-emitting diodes (LED's), photo-voltaic devices, photo-conductive devices, piezo-electric devices, electrostrictive devices, actuators, translators, rotators, linear and/or rotary stepper motors, linear and/or rotary servo systems, combinations thereof, and/or functional equivalents thereof. Several specific illustrative examples follow. An electronic and/or optical control signal may be applied to an optically thin semiconductor quantum well material provided on a fiber end face, for example, thereby altering the optical loss of the circumferential-mode resonator. An optical and/or electronic signal may be applied to an electro-optic material deposited on the resonator fiber segment, thereby altering the circumferential-mode resonator refractive index and therefore also altering a resonant frequency of the circumferential-mode resonator. A mechanical control signal may be applied via a piezo-electric, electro-static, or micro-electro-mechanical (MEM) control element to move a fiber-optic waveguide into or out of mechanical contact with the circumference of the circumferential-mode resonator, thereby altering the optical coupling between the circumferential-mode resonator and the fiber-optic waveguide. A mechanical control signal may be applied via a piezo-electric, electro-

static, or micro-electro-mechanical (MEM) control element to move a resonator loss element into or out of mechanical contact with the circumference of the circumferential-mode resonator, thereby altering the optical loss of the circumferential-mode resonator. The foregoing are exemplary only, and many other modulation schemes may be devised for application of control signals for modulating of circumferential-mode resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein. A portion of the modulator control element may reside on and/or within the alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device.

The application of a control signal to a modulator of a circumferential-mode resonator via a modulator control element enables controlled modulation of the optical power transmitted through the fiber-optic waveguide of the optical power control device. This may be accomplished in a variety of ways, depending on the nature of the modulator employed, and several specific examples follow. Modulating the optical loss of the circumferential-mode resonator between essentially zero loss and the so-called critical-coupling loss (wherein the circumferential-mode loss roughly equals the coupling between the transmission fiber and the circumferential-mode resonator) enables modulation of an optical wave that is resonant with a circumferential mode of the circumferential-mode resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the circumferential-mode optical loss constant while modulating the optical coupling between the fiber-optic waveguide and the circumferential-mode resonator. Alternatively, modulating a resonant frequency of a circumferential-mode having optical loss substantially equal to the critical-coupling loss may enable similar modulation of an optical wave as the circumferential-mode resonant frequency is moved out of and brought into resonance with the optical wave. The foregoing are exemplary only, and many other fiber-optic waveguide modulation schemes may be devised by suitable modulation of circumferential-mode resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

In addition to the fiber-optic waveguide and the circumferential-mode resonator (and possibly including a modulator and a modulator control element), an optical power control device according to the present invention may further comprise a secondary optical assembly positioned on the alignment device substantially tangentially engaged with the

circumferential-mode resonator fiber segment, as disclosed in applications A1 through A13, cited hereinabove. The secondary optical assembly may therefore be optically coupled to the circumferential-mode resonator, and coupled to the fiber-optic waveguide therethrough. The modulator (if present) may be employed to actively modulate the optical coupling between the secondary optical assembly and the fiber-optic waveguide through modulation of optical properties of the circumferential-mode resonator and/or coupling between the circumferential-mode resonator and the fiber-optic waveguide and/or the secondary optical assembly in a manner similar to that described hereinabove. Alternatively, the optical coupling/interactions between the fiber-optic waveguide, circumferential-mode optical resonator, and secondary optical assembly may be passive. The secondary optical assembly may comprise a second fiber-optic waveguide (thereby enabling controlled switching or passive routing of an optical wave propagating along the first fiber-optic waveguide to the second fiber-optic waveguide; Figs. 15A and 15B), a waveguide of another type, or the secondary optical assembly may comprise a second circumferential-mode optical resonator (thereby enabling, for example, controlled modification/modulation of the overall properties of the optical power control device, particularly the wavelength dependence of the control device). The secondary optical assembly may be positioned on and secured to the alignment device on the same alignment substrate as the first fiber-optic waveguide and first circumferential-mode resonator, or the alignment device may comprise a second alignment substrate with the secondary optical assembly positioned and secured thereto. Such a secondary optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the secondary optical assembly with the first circumferential-mode resonator when the optical power control device is assembled. The alignment device, including the first fiber-optic waveguide, the first circumferential-mode optical resonator, and the secondary optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using welding, fusion, adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system. A portion of the modulator control element (if present) may reside on and/or within the assembled alignment device, and access to the control element may

be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, windows, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

A specific example of an optical power control device according to the present invention suitable for routing optical signals is shown in Figs. 15A and 15B. Two fiber-optical waveguides 300 and 800 are shown coupled to the same circumferential-mode optical resonator 602. A propagating optical mode in fiber-optic waveguide 300 may be routed into fiber-optic waveguide 800 by transverse optical coupling of each waveguide to circumferential-mode resonator 602, depending on the wavelength of the propagating optical mode and the resonance wavelength(s) of circumferential-mode resonator 602. Routing of optical signals in this way may be passive, the wavelength-dependence of the routing relying on the optical properties of circumferential-mode resonator 602. Alternatively, routing of optical signals using a device as shown in Figs. 15A and 15B may be actively controlled, by active control of optical coupling of waveguide 300 and/or waveguide 800 to resonator 602, and/or active control of properties of resonator 602. Waveguides 300 and 800 and resonator 602 may be reproducibly, reliably, and stably positioned using a suitable alignment device comprising first and second alignment substrates 502 and 510 and may be hermetically sealed within as disclosed herein. The one or both ends of waveguides 300 and 800 may extend beyond the alignment device (Fig. 15A) for connecting to an optical power transmission system.

Instead of providing a modulator on the circumferential-mode resonator, a modulator (if present) may alternatively comprise a separate modulator optical assembly. Modulation of the optical properties of the modulator optical assembly (rather than modulation of the optical properties of the circumferential-mode resonator) serves to modulate the optical power transmitted through the fiber-optic waveguide. The modulator optical assembly may preferably be positioned in substantial tangential engagement with the circumferential-mode resonator fiber segment (and therefore optically coupled to the circumferential-mode resonator) and secured to the alignment device. The modulator optical assembly may comprise any of a wide variety of devices, including but not limited to: an optical gain and/or loss modulator, a non-linear optical device, an electro-optic device, an electro-absorptive device, a semiconductor device (including semiconductor heterostructures, such as quantum wells), a second fiber-optic or other transversely-

optically-coupled waveguide, a second circumferential-mode resonator (which may further comprise a modulator, as described above), composite structures comprising multi-layer dielectric stacks incorporating an electro-optic layer, combinations thereof, and/or functional equivalents thereof. The optical properties of the modulator optical assembly may be controlled and/or modulated to modulate the transmission of optical power through the fiber-optic waveguide as described hereinabove for a modulator provided on the circumferential-mode resonator. A control signal (electronic, optical, mechanical, or other) may be applied to the modulator optical assembly as described hereinabove, and the alignment device may comprise a component (a modulator control element) for delivering such control signals to the modulator optical assembly, as described hereinabove. The application of a control signal to the modulator optical assembly via a modulator control element enables controlled modulation of the optical power transmitted through the fiber-optic waveguide of the optical power control device and may be accomplished in a variety of ways, depending on the nature of the modulator employed. Several specific examples follow. Modulating the optical loss of an optical loss modulator optically coupled to the circumferential-mode resonator between essentially zero loss and the so-called critical-coupling loss (wherein the loss roughly equals the coupling between the transmission fiber and the circumferential-mode resonator) enables modulation of a propagating optical mode that is resonant with a circumferential mode of the circumferential-mode resonator between about 0% (substantially unattenuated transmission) and about 100% (substantially blocked transmission). A similar result may be obtained by keeping the modulator optical loss constant while modulating the optical coupling between the modulator optical assembly and the circumferential-mode resonator. Alternatively, modulating a resonant frequency of a second circumferential-mode resonator (part of the modulator optical assembly) may enable similar modulation of a propagating optical mode as the second circumferential-mode resonant frequency is moved out of and brought into resonance with the propagating optical mode. The foregoing are exemplary only, and many other fiber-optic waveguide modulation schemes may be devised by suitable modulation of circumferential-mode resonator optical properties while remaining within the scope of inventive concepts disclosed and/or claimed herein.

The modulator optical assembly may be positioned on and secured to the alignment device on the same alignment substrate as the fiber-optic waveguide and circumferential-mode resonator, or the alignment device may comprise a second alignment

substrate with the modulator optical assembly positioned and secured thereto. The modulator optical assembly and/or second alignment substrate may be suitably indexed or provided with mating alignment structure(s) to enable reproducible, reliable, and stable alignment of the modulator optical assembly with the circumferential-mode resonator when the optical power control device is assembled. The alignment device, including the fiber-optic waveguide, the circumferential-mode optical resonator, and the modulator optical assembly, may be sealed (preferably hermetically sealed) after assembly, as disclosed hereinabove. A cover, the second alignment substrate, or another functionally equivalent component may be positioned over the alignment grooves and sealed into place (using adhesives, epoxies, resins, polymers, solders, and/or the like), leaving only the two ends of the fiber-optic waveguide exposed for connecting to an optical power transmission system. A portion of the modulator control element may reside on and/or within the assembled alignment device, and access to the control element may be provided enabling control of the modulator after hermetic sealing of the alignment device. Such access may comprise feed-through connectors, access ports, embedded conductors and/or optical fibers, and the like for transmitting optical, electronic, or mechanical control signals.

In the alternative embodiment, a plurality of circumferential-mode resonator fiber segments are provided along a single optical fiber sufficiently close that each circumferential-mode resonator may be optically coupled longitudinally to its neighboring circumferential-mode resonators. A fiber-optic waveguide may be optically coupled to a first resonator fiber segment, and a second fiber-optic waveguide may be optically coupled to a second resonator fiber segment. Appropriate selection of a combination of resonant frequencies for each of the resonator fiber segments enables tailoring of the frequency dependence of the overall optical coupling between optical fiber and optical fiber via the plurality of resonator fiber segments. In this way optical power control devices having specifically designed/tailored frequency characteristics may be fabricated.

The alignment device, comprising one or more grooved and/or indexed alignment substrates, may be fabricated from a material sufficiently rigid to provide reliable, reproducible, and stable positioning of the fiber-optic waveguide, circumferential-mode resonator, and any secondary or modulator optical assembly that comprise the optical power control device. Preferred materials may include ceramics or semiconductors such as silicon or a III-V semiconductor, but other material (such as metals, alloys, glasses, crystalline materials, and dielectric materials) may be employed while remaining within

the scope of inventive concepts disclosed and/or claimed herein. The waveguide-alignment groove and the resonator-alignment groove may be formed by any suitable means for machining (or otherwise processing) the material used. A preferred method for providing the grooves is laser machining (most preferably ablative laser machining with an excimer laser), however, other fabrication techniques may be employed, such as lithographic patterning of a mask followed by wet (chemical) or dry (reactive ion) etching, electric discharge machining, plasma discharge machining, or single wire arc ablation. These same machining/processing techniques may be employed for providing other alignment and/or indexing structures on the alignment device (such as tabs, slots, pins, holes, grooves, and the like).

Laser machining has been set forth as a preferred method for spatially-selective removal of material from the optical fiber at various points in the fabrication process of fiber-optic waveguides and circumferential-mode resonator (for patterning etch masks, deposition masks, diffusion and/or doping masks, and so forth). While remaining within the scope of inventive concepts disclosed and/or claimed herein, other methods for patterned removal of material from the optical fiber may be employed, including but not limited to: lithographic methods, optical patterning of photosensitive materials and/or photo-resists, mechanical techniques, electric or plasma discharge techniques, combinations thereof, and/or functional equivalents thereof.

The techniques encompassed by the term "cylindrical processing" may be employed to produce fiber tapers that may in turn be employed for polarization-specific propagation of optical modes therethrough and transverse coupling of such modes to the circumferential optical modes of a circumferential-mode optical resonator. Cylindrical processing may be employed to produce a non-PM tapered optical fiber segment coupled on each end thereof to PM optical fiber. The technique involves splicing a section of standard (i.e., non-PM) single-mode fiber into a length of PM fiber and heating/pulling the standard fiber segment to form the tapered section. The two opposing sections of PM fiber must be rotationally aligned to high precision (1° or better), which can be achieved by the following process: (1) determine the orientation of one segment of PM fiber by rotating it under planar illumination and measuring the scattering pattern as a function of angle (i.e., measure the POL pattern of the fiber as is conventionally done in PM-capable fusion splicers); (2) fuse this section of PM fiber to a segment of standard single-mode fiber on which a portion of mask material such as hermetic carbon is provided; (3)

translate the fiber to bring the opposing (free) end of the coated standard fiber segment into the lithography exposure apparatus, whilst preserving the angular orientation of the fiber; (4) employ the technique of cylindrical lithography to produce angular registration marks on coated section in the near proximity of the free end of the coated standard fiber segment; (5) measure the POL pattern of the second segment of PM fiber; (6) align the PM fiber with respect to the angular registration marks, and fuse the second PM fiber segment to the segment of standard fiber. This process would produce a fiber taper waveguide member appropriate for polarization selective coupling to a circumferential-mode resonator since minimal polarization randomization should occur for a propagating optical mode traversing the tapered segment, provided the spliced-in section of standard fiber is sufficiently short.

The present invention has been set forth in the forms of its preferred and alternative embodiments. It is nevertheless intended that modifications to the disclosed fiber-optic waveguides and methods of fabrication and use thereof may be made without departing from inventive concepts disclosed and/or claimed herein.

CLAIMS

What is claimed is:

1. A method for fabricating a fiber-optic waveguide, comprising the step of spatially selectively removing material from a cladding layer of a transverse-optical-coupling fiber segment of a waveguide optical fiber so as to form a transverse-optical-coupling portion of a cladding layer surface thereof, so that a remaining portion of the cladding layer is asymmetrically disposed about at least a portion of a core of the waveguide optical fiber so as to enable a portion of a propagating optical mode propagating therethrough to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment while being transversely substantially encompassed by respective cladding layers of two longitudinally adjacent fiber segments of the waveguide optical fiber.

2. A method for fabricating a fiber-optic waveguide as recited in Claim 1, wherein the cladding-material-removing step includes spatially-selective etching of material from the cladding layer of the transverse-optical-coupling fiber segment of the waveguide optical fiber.

3. A method for fabricating a fiber-optic waveguide as recited in Claim 2, wherein the cladding-material-removing step includes the steps of:
   providing the waveguide optical fiber with a mask that substantially covers the two longitudinally adjacent segments of the waveguide optical fiber but covers only portions of a length and a circumference of the transverse-optical-coupling fiber segment of the waveguide optical fiber; and
   spatially-selectively etching the waveguide optical fiber, thereby asymmetrically removing material from the cladding layer of the transverse-optical-coupling fiber segment of the waveguide optical fiber.

4. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein:
   the mask-providing step includes spatially-selective removal of an outer fiber coating from portions of the length and circumference of the transverse-optical-coupling fiber segment; and
   the mask includes portions of the outer fiber coating remaining on the two longitudinally adjacent segments of the waveguide optical fiber and on portions of the transverse-optical-coupling fiber segment.

5. A method for fabricating a fiber-optic waveguide as recited in Claim 4, wherein the mask-providing step includes spatially-selective laser-machining of the outer fiber coating.

6. A method for fabricating a fiber-optic waveguide as recited in Claim 5, further including the step of partially rotating the waveguide optical fiber during laser machining so as to remove mask material from arcuate portions of a surface of the waveguide optical fiber extending partially around a circumference thereof.

7. A method for fabricating a fiber-optic waveguide as recited in Claim 5, further including the step of rotating the waveguide optical fiber within at least one rotation guide during laser machining so as to provide substantially concentric rotation during laser machining.

8. A method for fabricating a fiber-optic waveguide as recited in Claim 7, wherein the rotation guide includes at least one vacuum V-block.

9. A method for fabricating a fiber-optic waveguide as recited in Claim 7, wherein the rotation guide includes at least one capillary tube.

10. A method for fabricating a fiber-optic waveguide as recited in Claim 7, wherein the waveguide optical fiber rotates within a pair of rotation guides during laser machining.

11. A method for fabricating a fiber-optic waveguide as recited in Claim 5, further including the steps of:
rotating the waveguide optical fiber during laser machining, and
modulating a laser used for laser machining synchronously with rotation of the waveguide optical fiber so as to remove mask material from arcuate portions of a surface of the waveguide optical fiber extending partially around a circumference thereof.

12. A method for fabricating a fiber-optic waveguide as recited in Claim 5, wherein the outer fiber coating includes a polymeric jacket and laser machining is performed with a UV-emitting excimer laser.

13. A method for fabricating a fiber-optic waveguide as recited in Claim 5, wherein the outer fiber coating includes a carbon coating and laser machining is performed with a pulsed laser.

14. A method for fabricating a fiber-optic waveguide as recited in Claim 5, wherein the outer fiber coating includes a carbon coating and laser machining is performed with a substantially continuous laser.

15. A method for fabricating a fiber-optic waveguide as recited in Claim 5, wherein the outer fiber coating includes a photo-resist material.

16. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein the mask-providing step includes spatially-selective deposition of an outer fiber coating on the two longitudinally adjacent segments of the waveguide optical fiber and on portions of the length and circumference of the transverse-optical-coupling fiber segment, and the mask includes the outer fiber coating thus deposited.

17. A method for fabricating a fiber-optic waveguide as recited in Claim 16, wherein the mask-providing step includes spatially-selective metal vapor deposition of the outer fiber coating.

18. A method for fabricating a fiber-optic waveguide as recited in Claim 17, wherein shadow masking techniques are employed to implement the spatially-selective metal vapor deposition of the outer fiber coating.

19. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein the spatially-selective etching step is performed using aqueous hydrofluoric acid.

20. A method for fabricating a fiber-optic waveguide as recited in Claim 19, wherein the aqueous hydrofluoric acid includes between about 5% HF and about 50% HF buffered with NH_4F.

21. A method for fabricating a fiber-optic waveguide as recited in Claim 19, wherein the aqueous hydrofluoric acid includes between about 7% HF and about 8% HF buffered with between about 30% NH_4F and about 40% NH_4F.

22. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein the waveguide optical fiber is polarization-maintaining optical fiber, including longitudinally extending stressor elements disposed within the cladding layer in substantially opposing positions about the core, the stressor elements being etched at a slower rate than the cladding layer so as to yield transversely protruding passive alignment structures as a result of the cladding-material-removing step.

23. A method for fabricating a fiber-optic waveguide as recited in Claim 22, wherein the passive alignment structures are adapted for engaging longitudinally adjacent fiber segments of a fiber-ring circumferential-mode optical resonator so as to enable:
substantially reproducible substantially tangential engagement of the transverse-optical-coupling fiber segment and a fiber-ring circumferential-mode optical resonator; and
substantially reproducible transverse optical coupling between a circumferential optical mode of the fiber-ring resonator and the propagating optical mode of the transverse-optical-coupling fiber segment.

24. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein the cladding-material-removing step further includes the step of removing the mask from the waveguide optical fiber.

25. A method for fabricating a fiber-optic waveguide as recited in Claim 3, wherein the cladding-material-removing step further includes the step of controlling a shape and size of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment by selecting a shape and a size of an area of the transverse-optical-coupling fiber segment left uncovered by the mask-providing step.

26. A method for fabricating a fiber-optic waveguide as recited in Claim 25, wherein a width and a circumferential extent of the area of the transverse-optical-coupling fiber segment left uncovered by the mask-providing step are selected so as to control the shape and size of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment.

27. A method for fabricating a fiber-optic waveguide as recited in Claim 25, wherein:
the area left uncovered by the mask-providing step includes a plurality of arcuate segments of the cladding layer surface, the arcuate segments extending partially around the circumference of the waveguide optical fiber and being separated from adjacent arcuate segments by intervening portions of the mask; and
number, widths, circumferential extents, and spacings from adjacent arcuate segments are selected for the plurality of arcuate segments so as to control the shape and size of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment.

28. A method for fabricating a fiber-optic waveguide as recited in Claim 1, wherein the cladding-material-removing step further includes the step of controlling a shape and size of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment.

29. A method for fabricating a fiber-optic waveguide as recited in Claim 28, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a saddle-like shape, the saddle-like shape having a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a convex transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment.

30. A method for fabricating a fiber-optic waveguide as recited in Claim 29, wherein the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface is adapted for receiving and substantially tangentially engaging a circumferential-mode optical resonator so as to enable transverse optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

31. A method for fabricating a fiber-optic waveguide as recited in Claim 29, wherein the convex transverse-sectional shape of the coupling portion of the cladding layer surface is adapted for enabling substantial tangential engagement of the coupling portion of the cladding layer surface and a fiber-ring circumferential-mode optical resonator so as to enable transverse optical coupling between a circumferential optical mode of the fiber-ring resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

32. A method for fabricating a fiber-optic waveguide as recited in Claim 28, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a pit-like shape, the pit-like shape having a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a concave transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment.

33. A method for fabricating a fiber-optic waveguide as recited in Claim 32, wherein the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface is adapted for receiving and substantially tangentially engaging a

circumferential-mode optical resonator so as to enable transverse optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

34. A method for fabricating a fiber-optic waveguide as recited in Claim 32, wherein the concave transverse-sectional shape of the coupling portion of the cladding layer surface is adapted for enabling substantial tangential engagement of the coupling portion of the cladding layer surface and a micro-disk circumferential-mode optical resonator so as to enable transverse optical coupling between a circumferential optical mode of the micro-disk resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

35. A method for fabricating a fiber-optic waveguide as recited in Claim 28, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a substantially flat transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment, the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface being adapted for receiving and substantially tangentially engaging a whispering-gallery-mode optical resonator so as to enable transverse optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

36. A method for fabricating a fiber-optic waveguide as recited in Claim 1, wherein the cladding-material-removing step further includes the step of controlling the amount of cladding material removed from the transverse-optical-coupling fiber segment.

37. A method for fabricating a fiber-optic waveguide as recited in Claim 36, wherein the controlling step includes the steps of:

monitoring optical loss of the waveguide optical fiber during the cladding-material-removing step; and

terminating the cladding-material-removing step in response to monitored optical loss of the waveguide optical fiber reaching a pre-selected level.

38. A method for fabricating a fiber-optic waveguide as recited in Claim 37, wherein the pre-selected optical loss level is less than about 30 dB.

39. A method for fabricating a fiber-optic waveguide as recited in Claim 37, wherein the pre-selected optical loss level is less than about 10 dB.

40. A method for fabricating a fiber-optic waveguide as recited in Claim 37, wherein the pre-selected optical loss level is less than about 3 dB.

41. A method for fabricating a fiber-optic waveguide as recited in Claim 37, wherein the pre-selected optical loss level is less than about 1 dB.

42. A method for fabricating a fiber-optic waveguide as recited in Claim 36, wherein a minimum distance between the core of the waveguide optical fiber and the coupling portion of the cladding layer surface is less than about 10 μm as a result of the cladding-material-removing step.

43. A method for fabricating a fiber-optic waveguide as recited in Claim 36, wherein the core of the waveguide optical fiber is partially exposed as a result of the cladding-material-removing step.

44. A fiber-optic waveguide fabricated by the method of any one of Claims 1 through 43.

45. A fiber-optic waveguide, comprising:

a transverse-optical-coupling fiber segment including a core and a cladding layer;

a first longitudinally adjacent fiber segment including a core and a cladding layer, the cladding layer substantially surrounding the core and transversely substantially encompassing a propagating optical mode propagating through the first adjacent fiber segment, the first adjacent fiber segment being joined at an end thereof to a first end of the transverse-optical-coupling fiber segment; and

a second longitudinally adjacent fiber segment including a core and a cladding layer, the cladding layer substantially surrounding the core and substantially transversely encompassing a propagating optical mode propagating through the second adjacent fiber segment, the second adjacent fiber segment being joined at an end thereof to a second end of the transverse-optical-coupling fiber segment,

the core of the first adjacent fiber segment, the core of the transverse-optical-coupling fiber segment, and the core of the second adjacent fiber segment forming a substantially continuous core of the fiber-optic waveguide so as to enable a propagating optical mode to propagate therethrough,

the cladding layer of the transverse-optical-coupling fiber segment being asymmetrically disposed about at least a portion of the core thereof so as to

provide a coupling portion of a cladding layer surface of the transverse-optical-coupling fiber segment, the transverse-optical-coupling segment being thereby adapted for enabling an evanescent portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment.

46. A fiber-optic waveguide as recited in Claim 45, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a saddle-like shape, having a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a convex transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment.

47. A fiber-optic waveguide as recited in Claim 46, wherein the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface is adapted for receiving and substantially tangentially engaging a circumferential-mode optical resonator so as to enable evanescent optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

48. A fiber-optic waveguide as recited in Claim 46, wherein the convex transverse-sectional shape of the coupling portion of the cladding layer surface is adapted for enabling substantial tangential engagement of the coupling portion of the cladding layer surface and a fiber-ring circumferential-mode optical resonator so as to enable evanescent optical coupling between a circumferential optical mode of the fiber-ring resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

49. A fiber-optic waveguide as recited in Claim 45, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a pit-like shape, having a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a concave transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment.

50. A fiber-optic waveguide as recited in Claim 49, wherein the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface is adapted for

receiving and substantially tangentially engaging a whispering-gallery-mode optical resonator so as to enable evanescent optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

51. A fiber-optic waveguide as recited in Claim 49, wherein the concave transverse-sectional shape of the coupling portion of the cladding layer surface is adapted for enabling substantial tangential engagement of the coupling portion of the cladding layer surface and a micro-disk circumferential-mode optical resonator so as to enable evanescent optical coupling between a circumferential optical mode of the micro-disk resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

52. A fiber-optic waveguide as recited in Claim 45, wherein the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment has a concave longitudinal-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment and a substantially flat transverse-sectional shape near at least a portion of the core of the transverse-optical-coupling fiber segment, the concave longitudinal-sectional shape of the coupling portion of the cladding layer surface being adapted for receiving and substantially tangentially engaging a circumferential-mode optical resonator so as to enable evanescent optical coupling between a circumferential optical mode of the resonator and the propagating optical mode at the transverse-optical-coupling fiber segment.

53. A fiber-optic waveguide as recited in Claim 45, wherein a thickness of the cladding layer between the coupling portion of the cladding layer surface and the core of the transverse-optical-coupling fiber segment yields a pre-selected level of optical loss of the transverse-optical-coupling fiber segment.

54. A fiber-optic waveguide as recited in Claim 53, wherein the pre-selected optical loss level is between about 0.1 dB and about 30 dB.

55. A fiber-optic waveguide as recited in Claim 53, wherein the pre-selected optical loss level is between about 0.1 dB and about 10 dB.

56. A fiber-optic waveguide as recited in Claim 53, wherein the pre-selected optical loss level is between about 0.1 dB and about 3 dB.

57. A fiber-optic waveguide as recited in Claim 53, wherein the pre-selected optical loss level is between about 0.1 dB and about 1 dB.

58. A fiber-optic waveguide as recited in Claim 45, wherein a minimum distance between the core of the transverse-optical-coupling fiber segment and the coupling portion of the cladding layer surface is between about 0 μm and about 10 μm.

59. A fiber-optic waveguide as recited in Claim 58, wherein the core of the transverse-optical-coupling fiber segment is partially exposed.

60. A fiber-optic waveguide as recited in Claim 45, wherein the adjacent fiber segments and transverse-optical-coupling fiber segment are fabricated from polarization-maintaining optical fiber, and each of said segments further includes longitudinally extending stressor elements disposed within the respective cladding layer in substantially opposing positions about the respective core, the stressor elements of the transverse-optical-coupling fiber segment serving as transversely protruding passive alignment structures.

61. A fiber-optic waveguide as recited in Claim 60, wherein the passive alignment structures are adapted for engaging longitudinally adjacent fiber segments of a fiber-ring whispering-gallery-mode optical resonator so as to enable reproducible substantially tangential engagement of the transverse-optical-coupling fiber segment and a fiber-ring circumferential-mode optical resonator and so as to enable reproducible transverse optical coupling between a circumferential optical mode of the fiber-ring resonator and the propagating optical mode of the transverse-optical-coupling fiber segment.

62. A resonant optical modulator assembly, comprising:

an alignment member, the alignment member including a waveguide-alignment groove and a resonator-alignment groove;

a transmission fiber-optic waveguide adapted for transmitting therethrough an optical signal carried by a waveguide optical mode, the transmission fiber-optic waveguide being positioned within the waveguide-alignment groove, being secured to the alignment member, and comprising

a transverse-optical-coupling fiber segment comprising a core and a cladding layer,

a first longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and transversely substantially encompassing a propagating optical mode propagating through the first adjacent fiber segment, the first adjacent fiber segment being joined at an end thereof to a first end of the transverse-optical-coupling fiber segment, and

a second longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and substantially transversely encompassing a propagating optical mode propagating through the second adjacent fiber segment, the second adjacent fiber segment being joined at an end thereof to a second end of the transverse-optical-coupling fiber segment,

the core of the first adjacent fiber segment, the core of the transverse-optical-coupling fiber segment, and the core of the second adjacent fiber segment forming a substantially continuous core of the fiber-optic waveguide so as to enable a propagating optical mode to propagate therethrough,

the cladding layer of the transverse-optical-coupling fiber segment being asymmetrically disposed about at least a portion of the core thereof so as to provide a coupling portion of a cladding layer surface of the transverse-optical-coupling fiber segment, the transverse-optical-coupling segment being thereby adapted for enabling a portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment;

an optical resonator for supporting at least one resonant optical mode, the optical resonator being positioned within the resonator-alignment groove and secured to the alignment member so as to be transversely optically coupled to the transmission fiber-optic waveguide at the transverse-optical-coupling segment thereof; and

an optical modulator for modulating, in response to an applied control signal, a coupling condition between the transmission optical waveguide and the optical resonator so as to controllably modulate a level of transmission through the transmission optical waveguide of the optical signal when the waveguide optical mode is substantially resonant with at least one of the resonant optical modes, the

optical modulator being positioned so as to be transversely optically coupled to the optical resonator,

the waveguide-alignment groove and the resonator-alignment groove being positioned on the alignment member so as to substantially reproducibly establish and substantially stably maintain evanescent optical coupling between the optical resonator and the evanescent optical coupling segment of the transmission optical waveguide.

63. The resonant optical power control device as recited in Claim 62, wherein the optical resonator includes at least one fiber-ring resonator formed on a resonator optical fiber.

64. The resonant optical power control device as recited in Claim 62, wherein the optical resonator includes a micro-sphere connected to a tapered portion of a resonator optical fiber, the resonator optical fiber substantially coinciding with a symmetry axis of the micro-sphere and serving as a resonator alignment member within the resonator alignment groove.

65. The resonant optical power control device as recited in Claim 62, wherein the resonator-alignment groove and the waveguide-alignment groove are substantially perpendicular, and differ in depth so that the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment of fiber-optic waveguide is in contact with the circumference of the optical resonator when the fiber-optic waveguide and the optical resonator are positioned within the waveguide-alignment groove and the resonator-alignment groove, respectively.

66. The resonant optical power control device as recited in Claim 62, further comprising a cover sealed to the alignment member so as to isolate the fiber-optic waveguide and the optical resonator from a use environment.

67. A resonant optical filter assembly for an optical WDM system, comprising:

an alignment member, the alignment member including a first waveguide-alignment groove, a second waveguide-alignment groove, and a resonator-alignment groove;

a transmission fiber-optic waveguide adapted for transmitting therethrough at least one of a plurality optical signals, each optical signal being carried by a respective waveguide optical mode corresponding to an optical channel of the WDM system, the transmission fiber-optic waveguide being positioned within the first

waveguide-alignment groove and secured to the alignment member and having a transverse-optical-coupling segment, the transmission fiber-optic waveguide comprising

a transverse-optical-coupling fiber segment comprising a core and a cladding layer,

a first longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and transversely substantially encompassing a propagating optical mode propagating through the first adjacent fiber segment, the first adjacent fiber segment being joined at an end thereof to a first end of the transverse-optical-coupling fiber segment, and

a second longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and substantially transversely encompassing a propagating optical mode propagating through the second adjacent fiber segment, the second adjacent fiber segment being joined at an end thereof to a second end of the transverse-optical-coupling fiber segment,

the core of the first adjacent fiber segment, the core of the transverse-optical-coupling fiber segment, and the core of the second adjacent fiber segment forming a substantially continuous core of the fiber-optic waveguide so as to enable a propagating optical mode to propagate therethrough,

the cladding layer of the transverse-optical-coupling fiber segment being asymmetrically disposed about at least a portion of the core thereof so as to provide a coupling portion of a cladding layer surface of the transverse-optical-coupling fiber segment, the transverse-optical-coupling segment being thereby adapted for enabling an evanescent portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment;

a second transmission optical waveguide adapted for transmitting therethrough at least one of the plurality of optical signals, each optical signal being carried by a respective waveguide optical mode corresponding to an optical channel of the WDM system, the second transmission optical waveguide being positioned

within the second waveguide-alignment grooves and secured to the alignment member and having a transverse-optical-coupling segment; and

a resonant optical assembly including at least one optical resonator, the resonant optical assembly supporting at least one resonant optical mode and being positioned within the resonator-alignment groove and secured to the alignment member so as to be transversely optically coupled to the transmission fiber-optic waveguide and the second transmission optical waveguide at the respective transverse-optical-coupling segments thereof,

an optical signal entering the resonant optical filter assembly through one of the transmission fiber-optic waveguide and the second transmission optical waveguide and substantially resonant with at least one of the resonant optical modes being substantially transferred from the one to the other of the transmission fiber-optic waveguide and the second transmission optical waveguide and leaving the resonant optical filter assembly therethrough,

an optical signal entering the resonant optical filter assembly through one of the transmission fiber-optic waveguide and the second transmission optical waveguide and substantially non-resonant with any resonant optical mode supported by the resonant optical assembly substantially remaining within the one of the transmission fiber-optic waveguide and the second transmission optical waveguide and leaving the resonant optical filter assembly therethrough,

the first waveguide-alignment groove, the second waveguide-alignment groove, and the resonator-alignment groove being positioned on the alignment member so as to substantially reproducibly establish and substantially stably maintain evanescent optical coupling between the transmission fiber-optic waveguide and the resonant optical assembly and between the second transmission optical waveguide and the resonant optical assembly.

68. The resonant optical filter assembly as recited in Claim 67, wherein the optical resonator includes at least one fiber-ring resonator formed on a resonator optical fiber.

69. The resonant optical filter assembly as recited in Claim 67, wherein the optical resonator includes a micro-sphere connected to a tapered portion of a resonator optical fiber, the resonator optical fiber substantially coinciding with a symmetry axis of the micro-sphere and serving as a resonator alignment member within the resonator alignment groove.

70. The resonant optical filter assembly as recited in Claim 67, wherein the resonator-alignment groove and the first waveguide-alignment groove are substantially perpendicular, and differ in depth so that the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment of the transmission fiber-optic waveguide is transversely optically coupled to the resonant optical assembly when the transmission fiber-optic waveguide and the resonant optical assembly are positioned within the first waveguide-alignment groove and the resonator-alignment groove, respectively.

71. The resonant optical filter assembly as recited in Claim 67, further comprising a cover sealed to the alignment member so as to isolate the transmission fiber-optic waveguide, the second transmission optical waveguide, and the resonant optical assembly from a use environment.

72. The resonant optical filter assembly as recited in Claim 67, wherein the second transmission optical waveguide is a second transmission fiber-optic waveguide and comprises:

a transverse-optical-coupling fiber segment comprising a core and a cladding layer;

a first longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and transversely substantially encompassing a propagating optical mode propagating through the first adjacent fiber segment, the first adjacent fiber segment being joined at an end thereof to a first end of the transverse-optical-coupling fiber segment; and

a second longitudinally adjacent fiber segment comprising a core and a cladding layer, the cladding layer substantially surrounding the core and substantially transversely encompassing a propagating optical mode propagating through the second adjacent fiber segment, the second adjacent fiber segment being joined at an end thereof to a second end of the transverse-optical-coupling fiber segment,

the core of the first adjacent fiber segment, the core of the transverse-optical-coupling fiber segment, and the core of the second adjacent fiber segment forming a substantially continuous core of the fiber-optic waveguide so as to enable a propagating optical mode to propagate therethrough,

the cladding layer of the transverse-optical-coupling fiber segment being asymmetrically disposed about at least a portion of the core thereof so as to provide a coupling portion of a cladding layer surface of the transverse-optical-

coupling fiber segment, the transverse-optical-coupling segment being thereby adapted for enabling an evanescent portion of the propagating optical mode to extend transversely beyond at least a portion of the coupling portion of the cladding layer surface of the transverse-optical-coupling fiber segment.

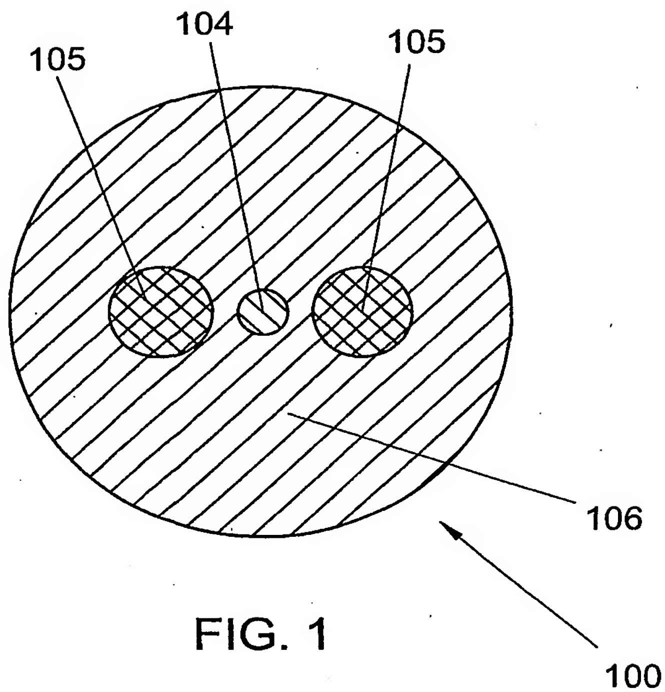

FIG. 1

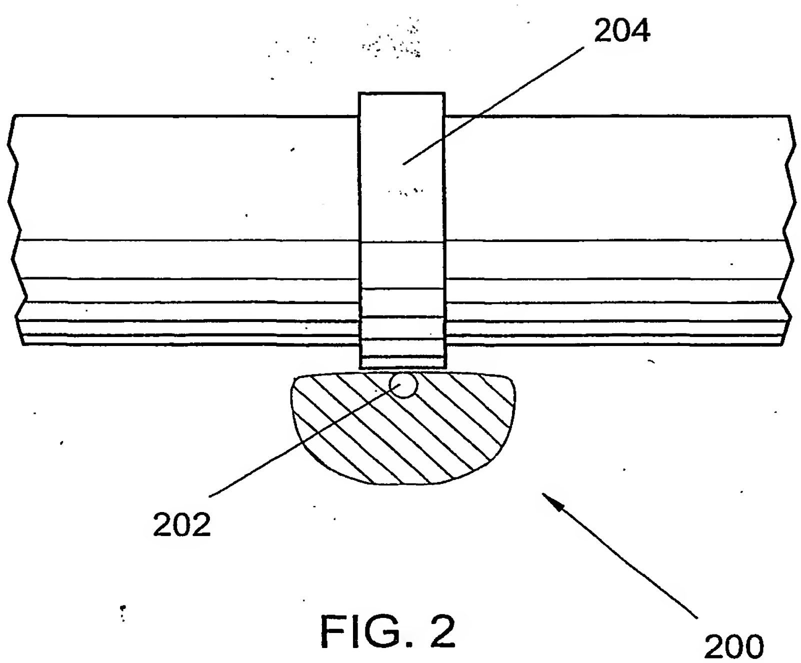

FIG. 2

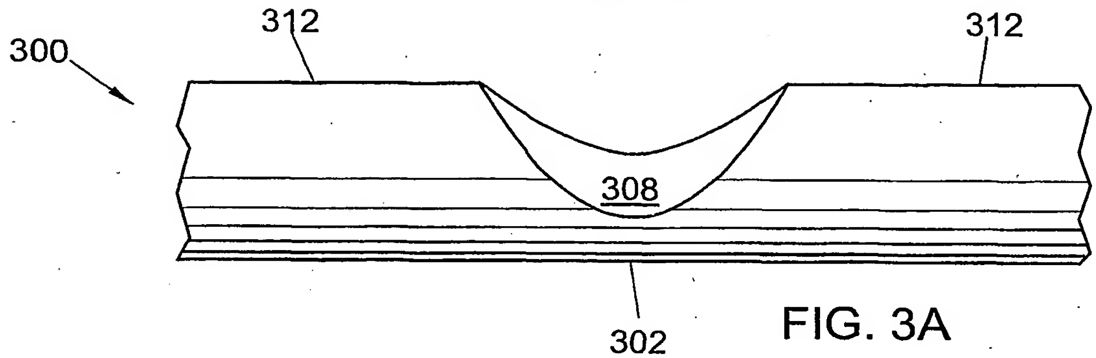

FIG. 3A

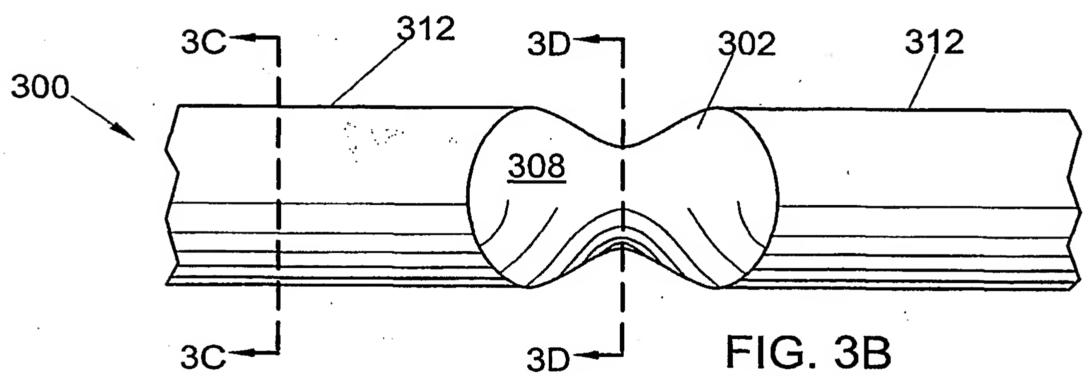

FIG. 3B

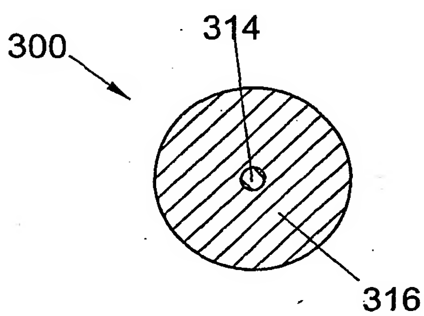

FIG. 3C

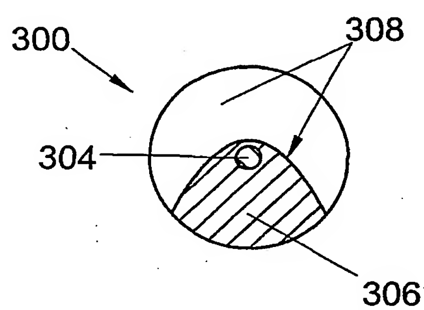

FIG. 3D

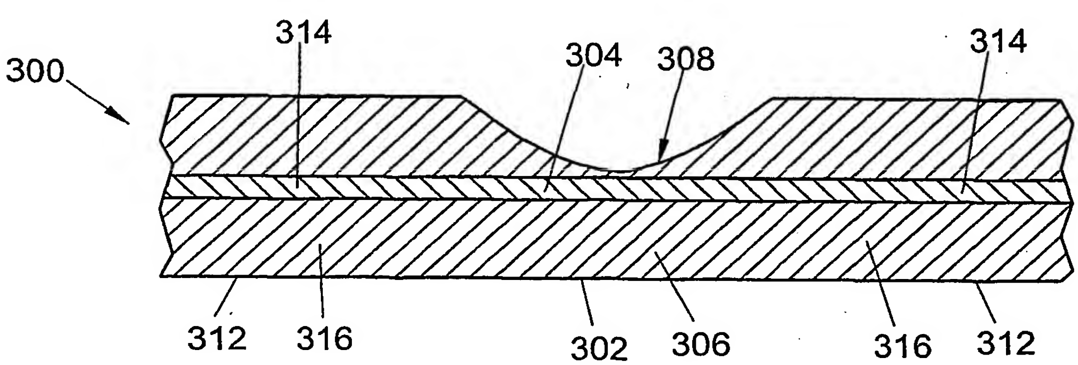

FIG. 3E

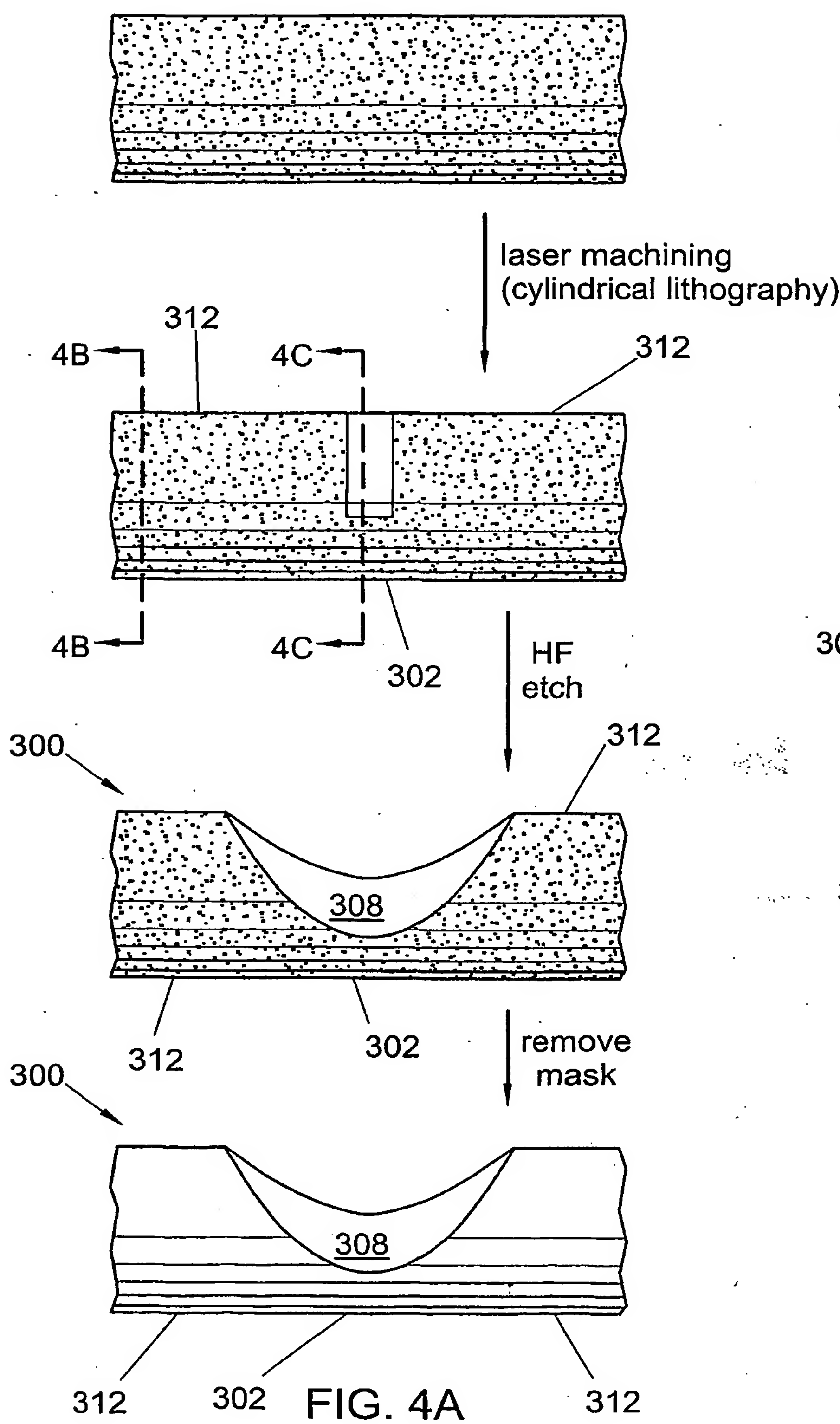

FIG. 4A

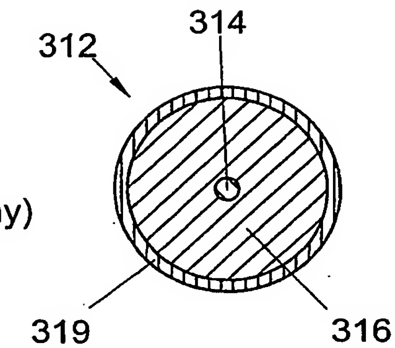

FIG. 4B

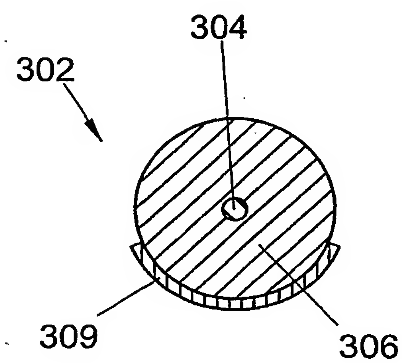

FIG. 4C

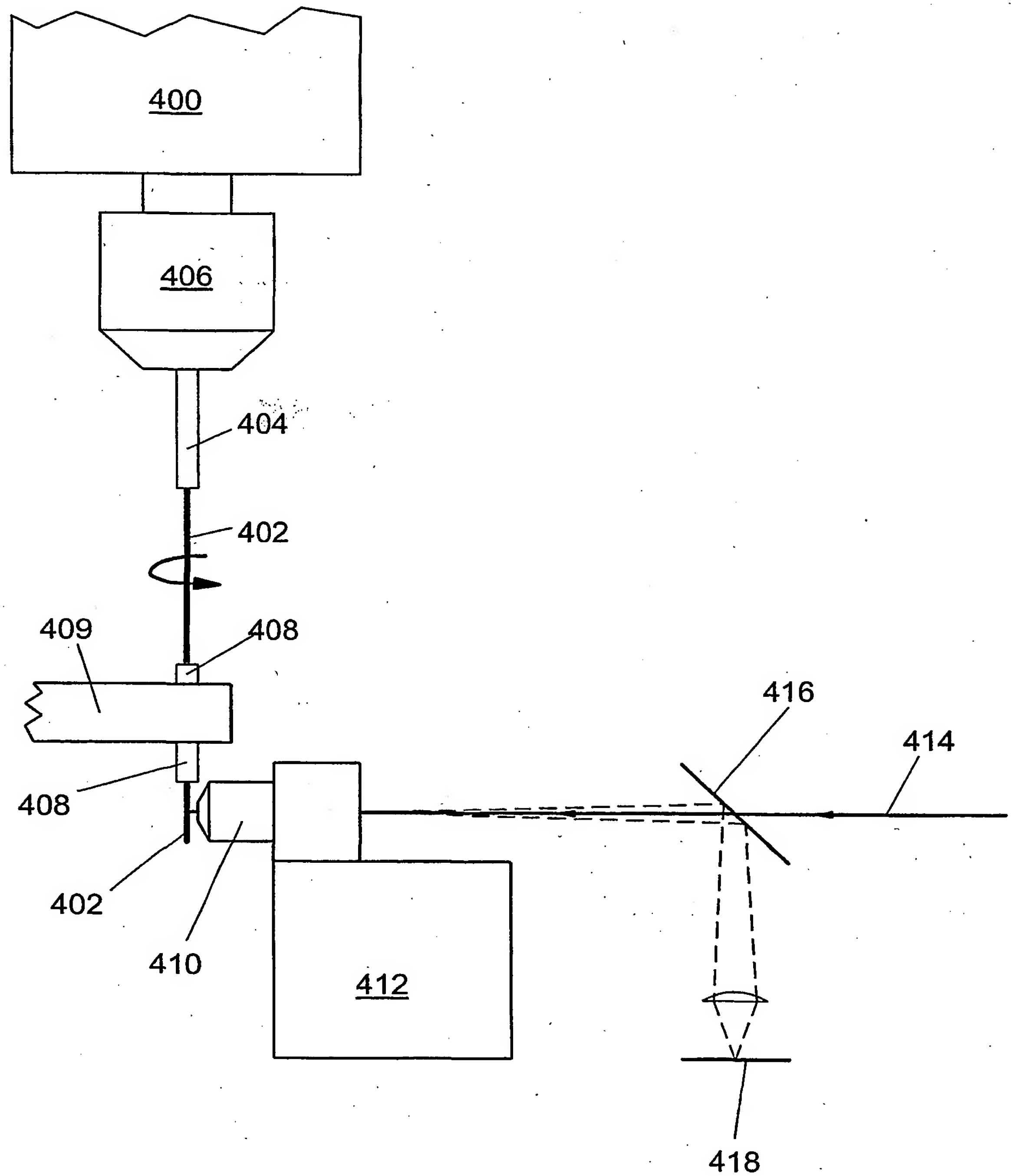

FIG. 5

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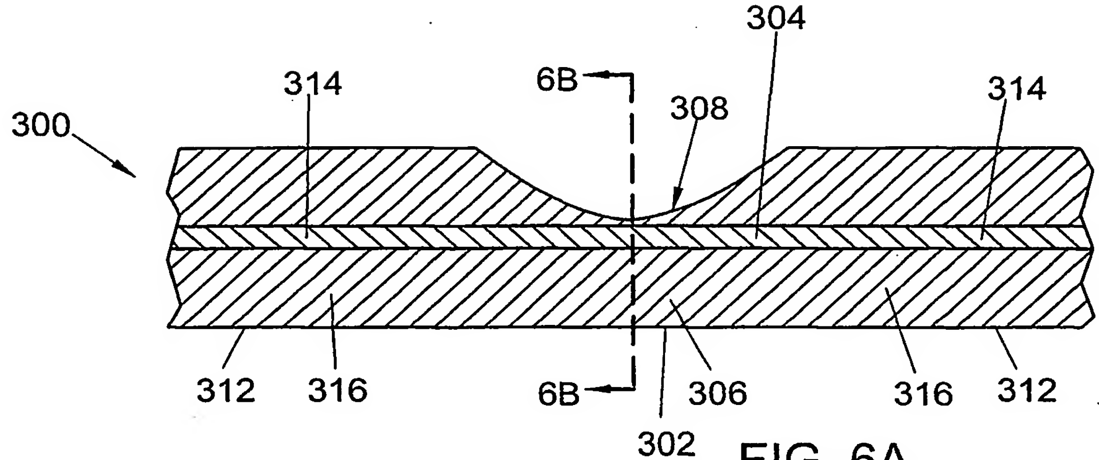

FIG. 6A

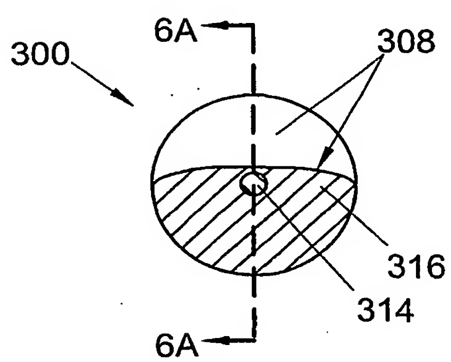

FIG. 6B

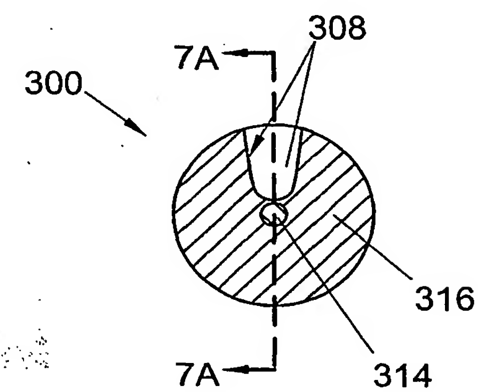

FIG. 7B

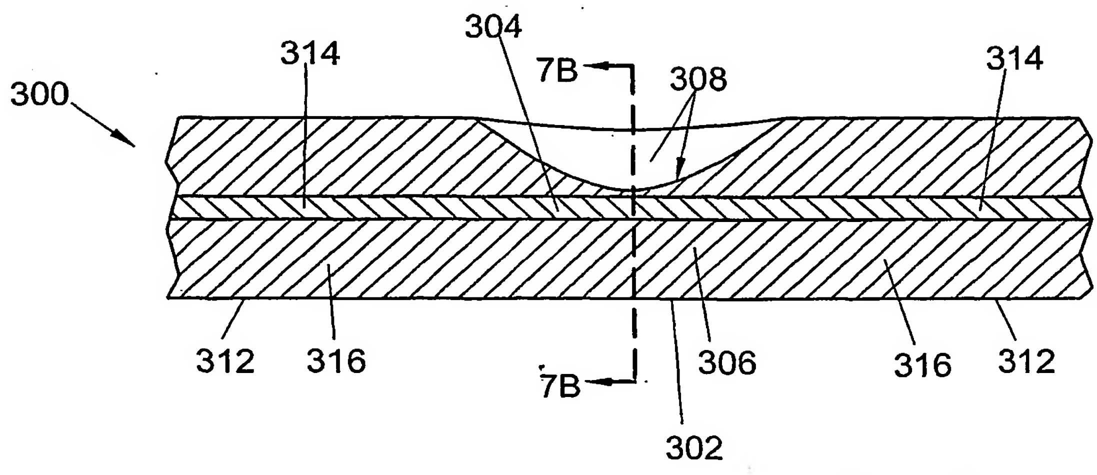

FIG. 7A

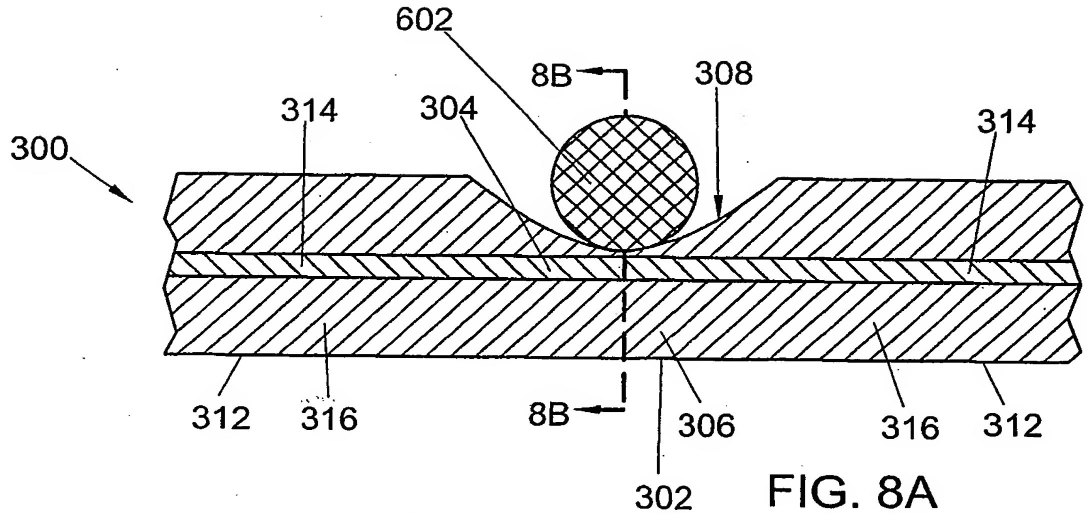

FIG. 8A

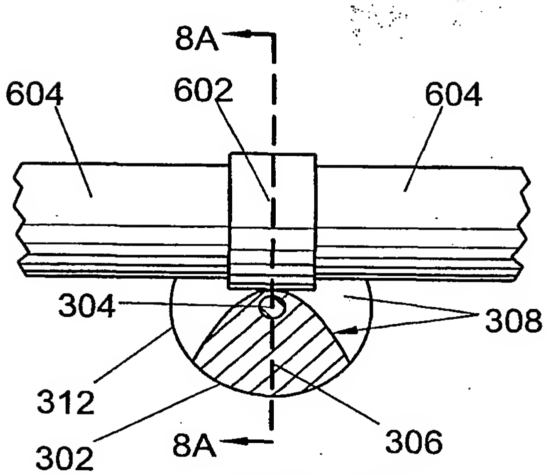

FIG. 8B

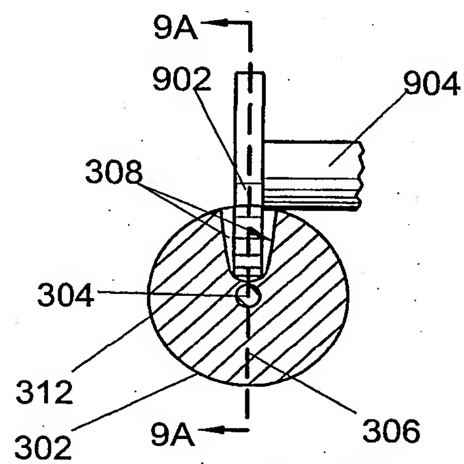

FIG. 9B

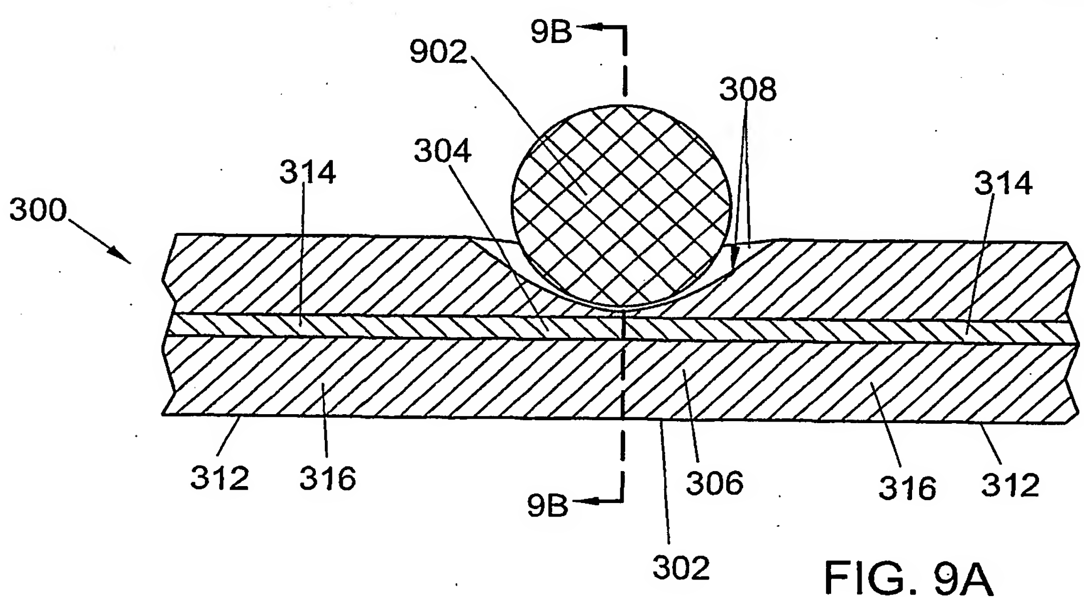

FIG. 9A

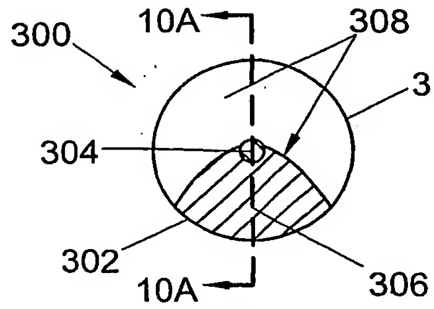

FIG. 10B

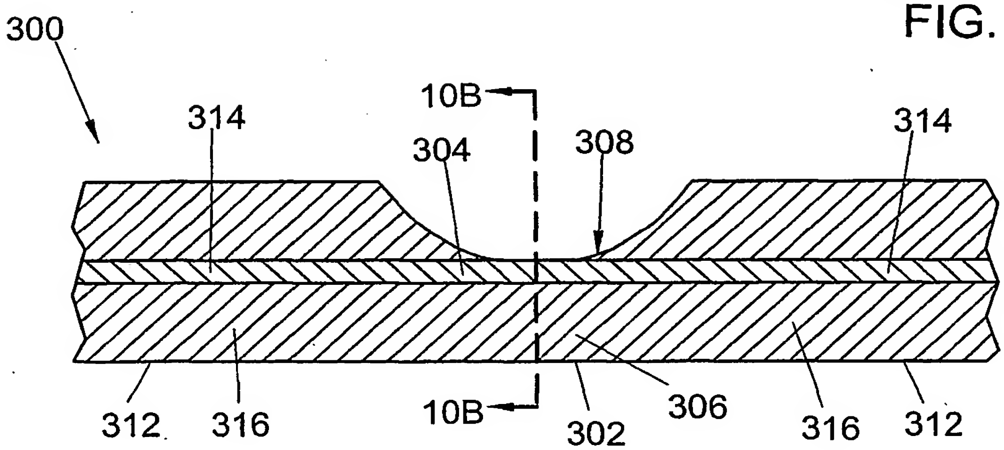

FIG. 10A

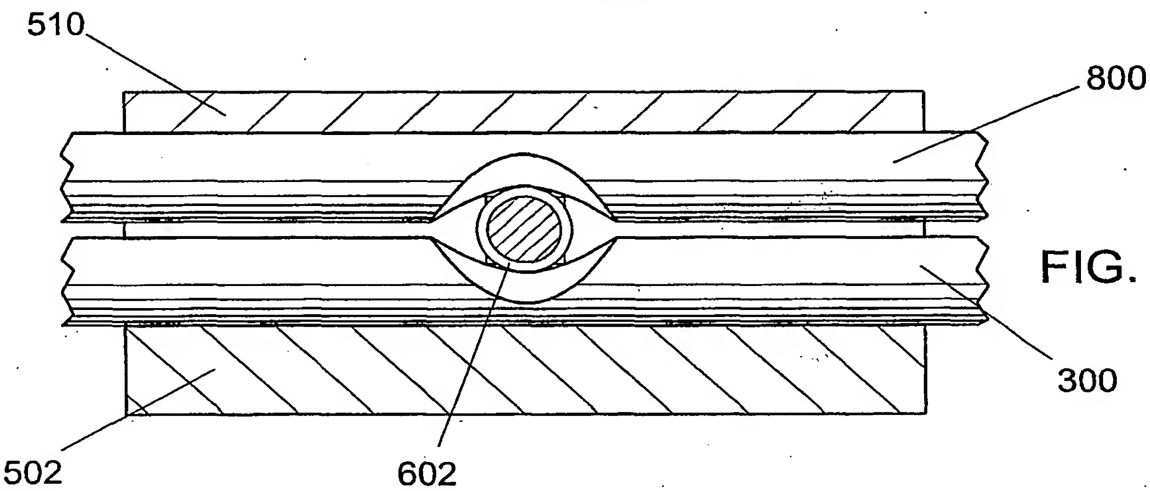

FIG. 15A

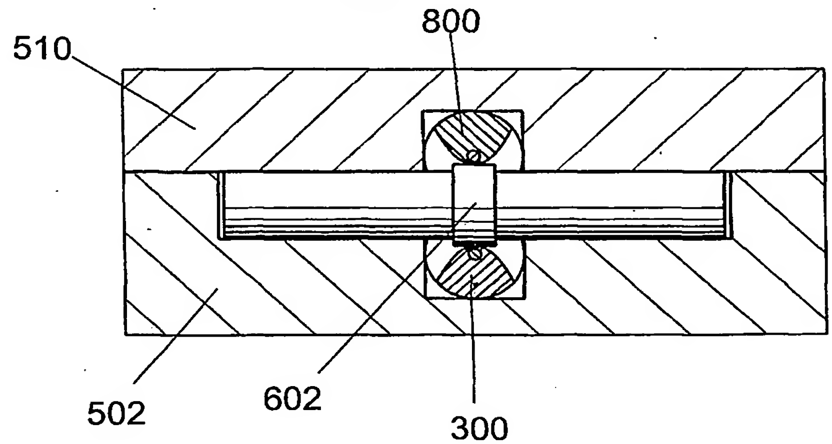

FIG. 15B

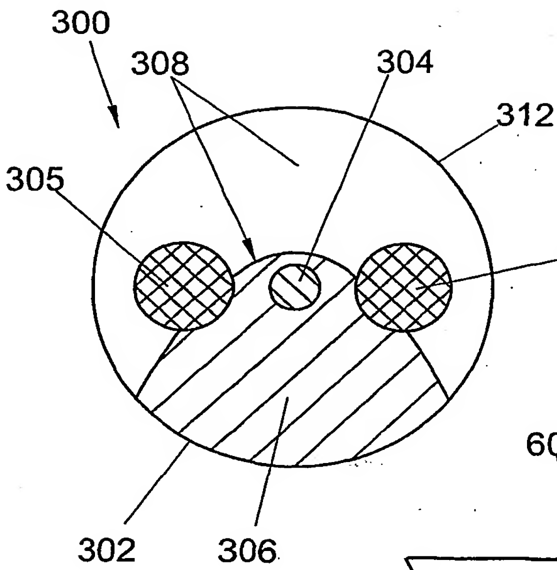

FIG. 11A

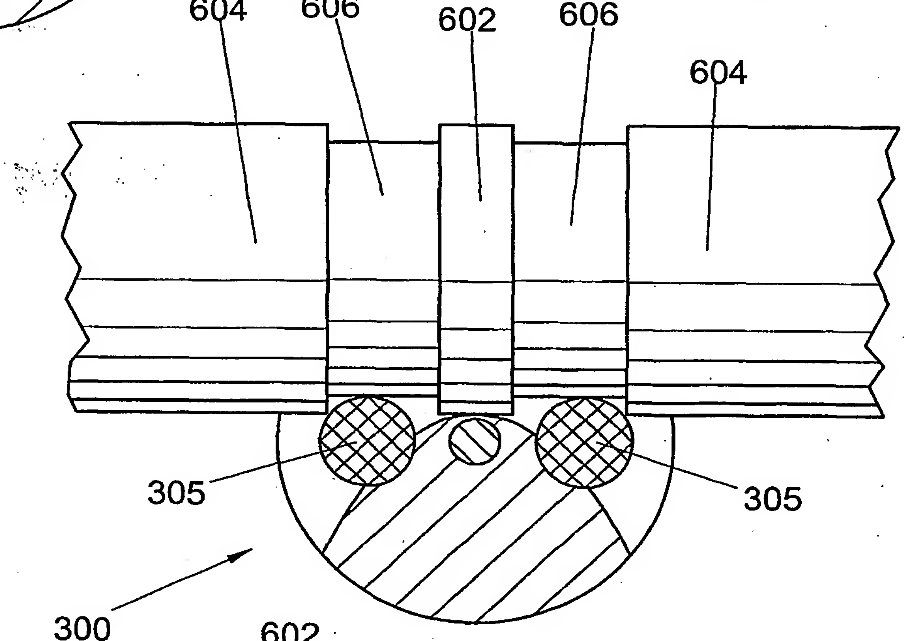

FIG. 11B

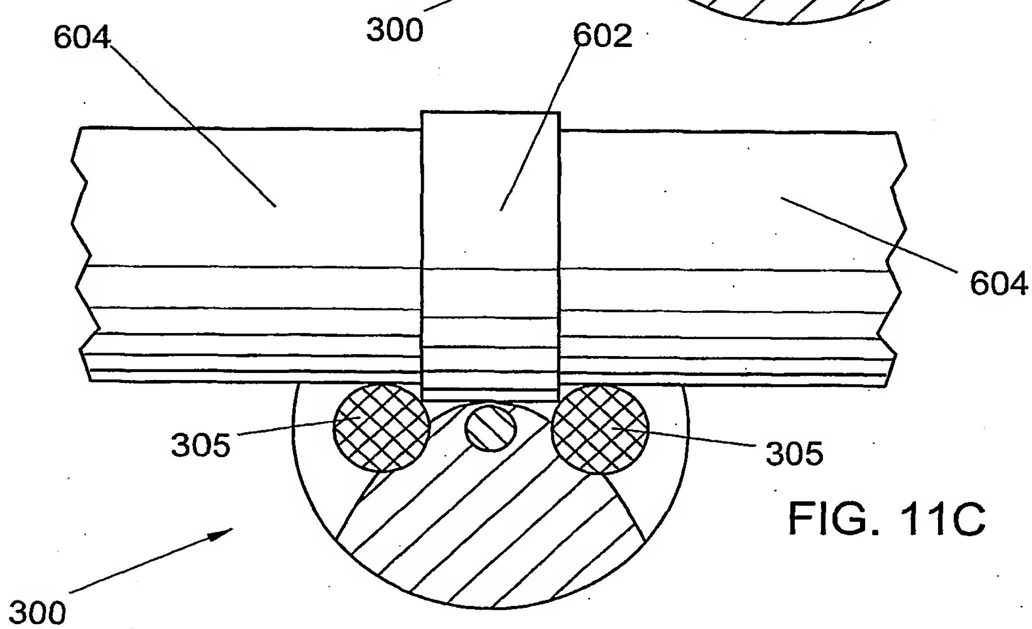

FIG. 11C

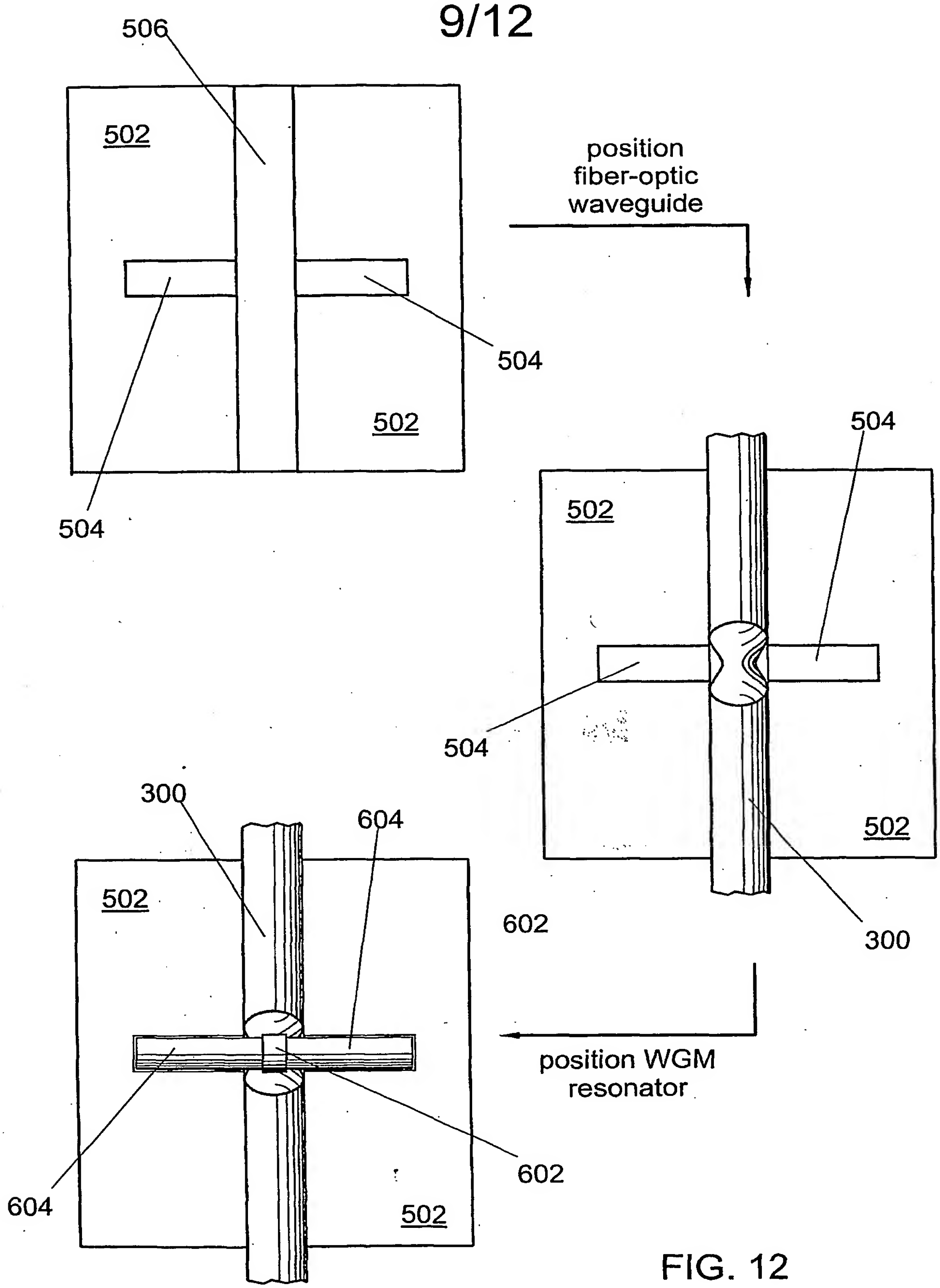
506
502
502
504
504
position
fiber-optic
waveguide
504
502
504
502
300
300
604
502
602
position WGM
resonator
604
602
502

FIG. 12

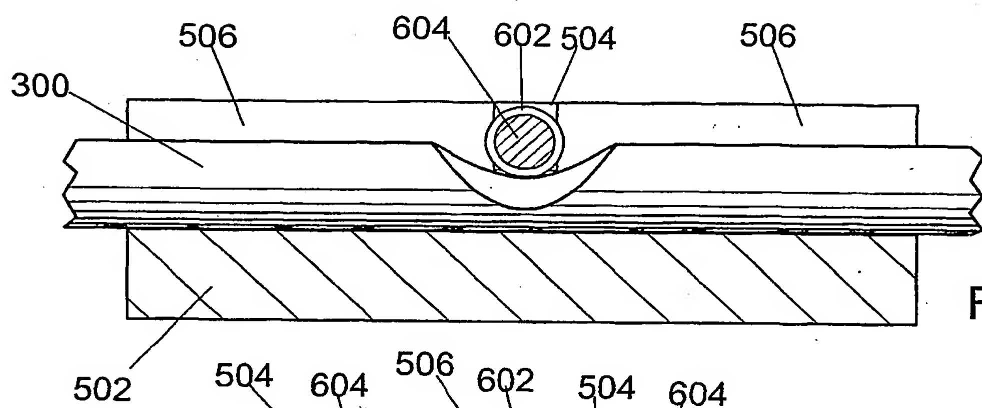

FIG. 13A

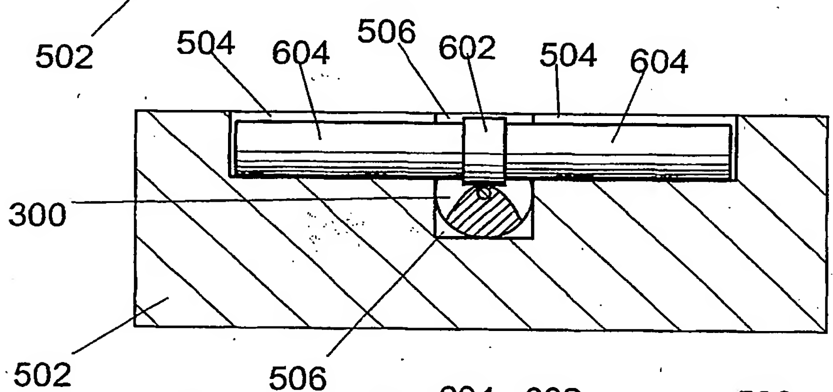

FIG. 13B

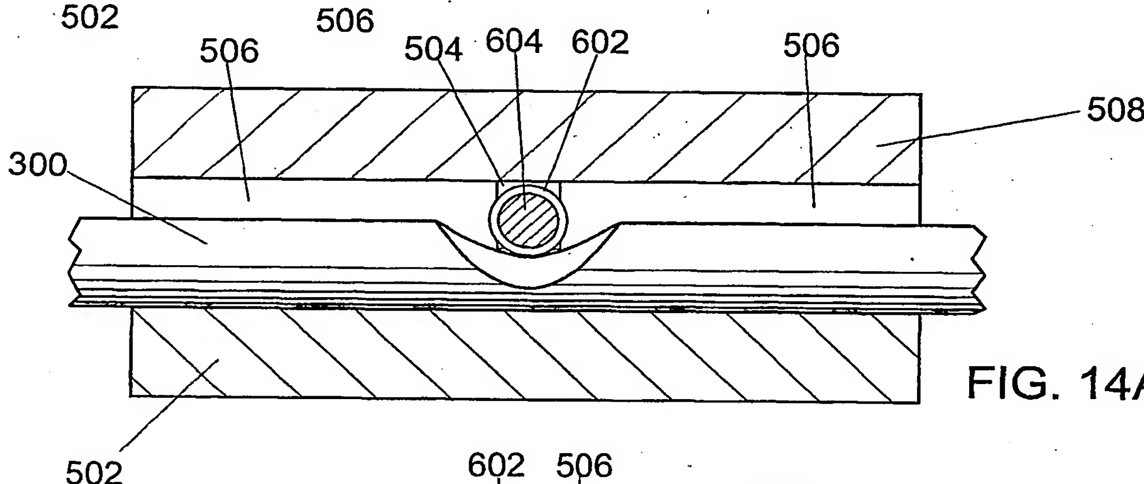

FIG. 14A

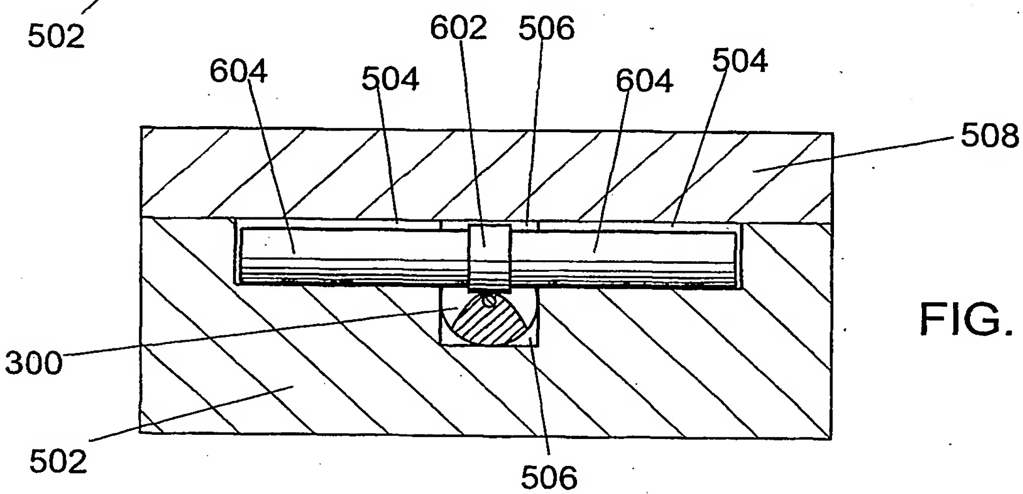

FIG. 14B

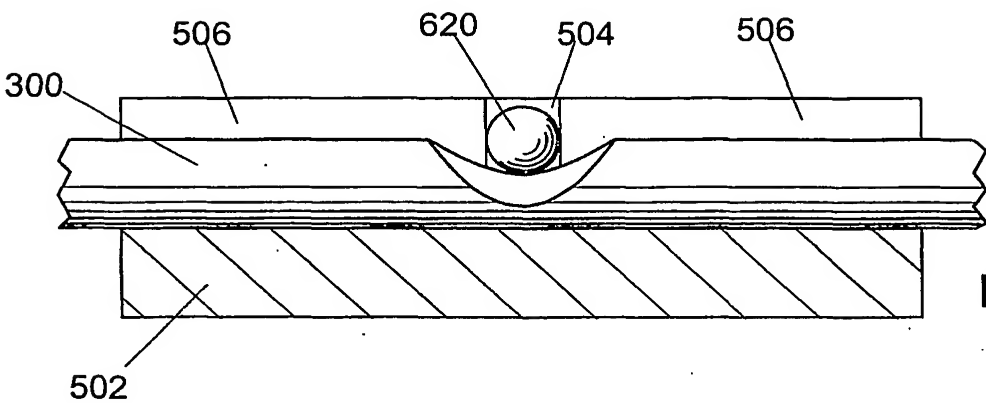

FIG. 16A

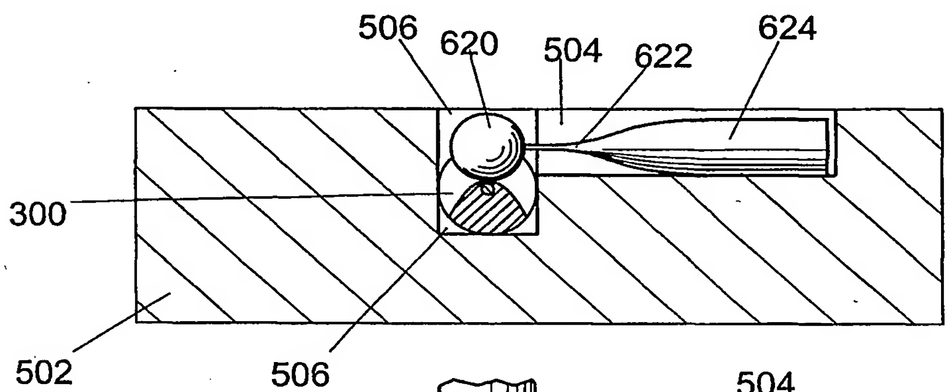

FIG. 16B

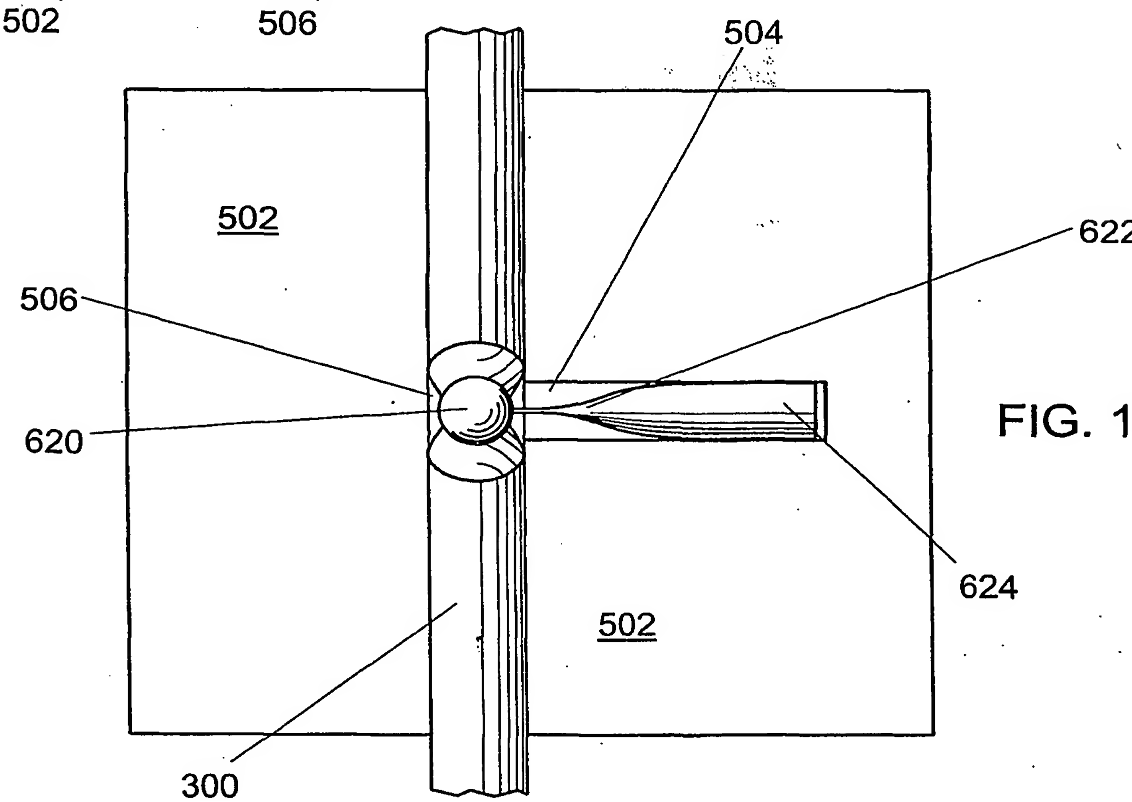

FIG. 16C

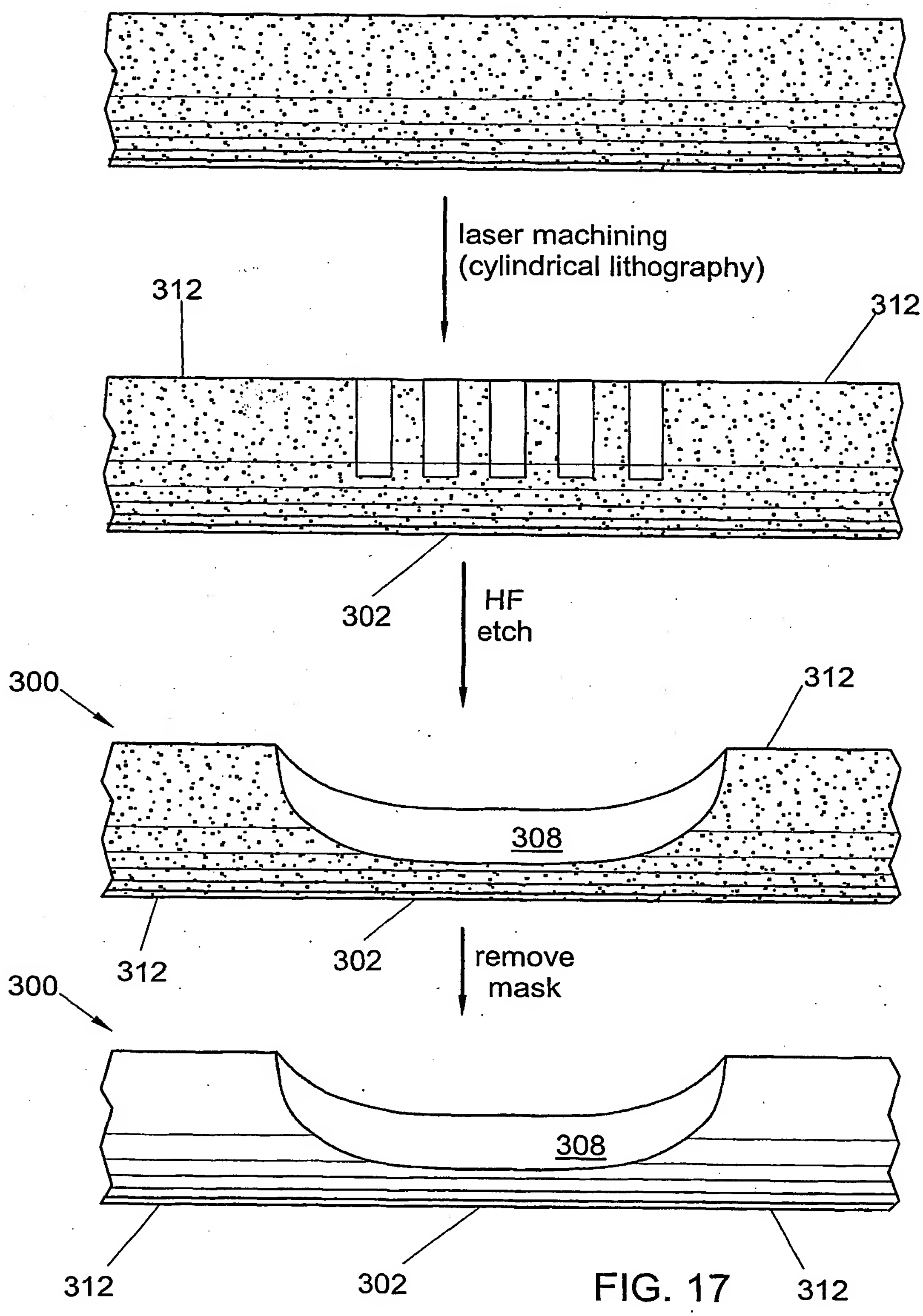
laser machining
(cylindrical lithography)
312
312
302
HF
etch
300
312
308
312
302
remove
mask
300
308
312
302
312

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/25828

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 6/26; B81C 3/00, 5/00; B81B 7/02
US CL : 216/6, 12, 24, 49, 51, 83; 385/4, 15, 30, 146

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 216/6, 12, 24, 49, 51, 83; 385/4, 15, 30, 146

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EAST (USPAT, DERWENT, EPO, JPO, IBM TECH DISCL BULL.)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DUBREUIL, N. et al, Eroded monomode optical fiber for whispering-gallery mode excitation in fused-silica microspheres, Optics Letters, 15 April 1995, Vol. 20, No. 8, pp 813-815.	
A	PRESBY, H.M. et al, Laser micromachining of efficient fiber microlenses, Applied Optics, 20 June 1990, Vol.29, No. 18, pp 2692-2695.	5-14
A	MCCALL, S.L. et al, Whispering-gallery mode microdisk lasers, Appl. Phys. Lett., 20 January 1992, Vol.60, No. 3, pp 289-291.	
A	CAI, M. et al, Observaton of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system, Physical Review Letters, 3 July 2000, Vol.85, No. 1, pp 74-77.	
A	US 5,751,242 A (GOUTZOULIS et al) 12 May 1998 (12.05.1998).	
A	KNIGHT, J.C. et al, Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper, Optics Letters, 01 August 1997, Vol.22, No. 15, pp 1129-1131.	
A	US 4,798,738 A (MOORE et al) 17 January 1989 (17.01.1989).	

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 December 2001 (31.12.2001)	16 JAN 2002

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Anita Alanko
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/25828

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	FR 2,739,195 A1, 28 March 1997 (28.03.1997).	
A	EP 0098102 A1 (NATIONAL RESEARCH DEVELOPMENT CORPORATION) 11 January 1984 (11.01.1984).	
A	US 5,586,205 A (CHEN et al) 17 December 1996 (17.12.1996).	19
A	US 5,729,641 A (CHANDONNET et al) 17 March 1998 (17.03.1998).	

Form PCT/ISA/210 (second sheet) (July 1998)